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UPPER CRETACEOUS TO PLEISTOCENE SEQUENCE STRATIGRAPHY OF THE BEAUFORT – MACKENZIE AND BANKS ISLAND AREAS, NORTHWEST CANADA

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PREFACE

The Upper Cretaceous to Pleistocene succession of the Beaufort-Mackenzie Basin contains large volumes of oil and gas; consequently, the basin could be a major producer of hydrocarbons in the future. In order to evaluate the economic potential and the environmental safeguards needed to safely produce the hydrocarbons, an understanding of the stratigraphy is a first-order necessity in any basin analysis. This report presents a regional stratigraphic scheme based upon the analysis of about 250 wells and many thousands of kilometres of reflection seismic. Conventional lithostratigraphy was found to be inapplicable on a regional scale; instead, transgressive-regressive sequences are identified and named. Basic lithological descriptions and sedimentological interpretations are presented, and paleogeographic reconstructions are attempted for various time periods. This report will be the foundation for future research, and the work presented here has already been used by the Geological Survey of Canada in evaluations of the hydrocarbon potential of the basin.

Elkanah A. Babcock
Assistant Deputy Minister
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PRÉFACE

Comme la succession datant du Crétacé supérieur au Pléistocène du bassin de Beaufort-Mackenzie contient de grandes quantités de pétrole et de gaz, ce bassin pourrait, par conséquent, être un important producteur d'hydrocarbures dans l'avenir. Afin d'évaluer le potentiel économique et les précautions environnementales à prendre pour extraire en toute sécurité les hydrocarbures, il est essentiel de connaître la stratigraphie du bassin. Ce rapport présente un schéma stratigraphique régional basé sur l'analyse de données provenant d'environ 250 puits et de levés de sismique réflexion couvrant des milliers de kilomètres. Comme il s'est avéré impossible d'appliquer à une échelle régionale la lithostratigraphie classique, ce sont plutôt les séquences transgressives-régressives qui ont été identifiées et désignées. Des descriptions lithologiques de base et des interpétations sédimentologiques sont présentées, et des reconstitutions paléogéographiques sont proposées pour diverses époques. Le présent rapport servira de base aux recherches futures et les travaux présentés ici ont déjà été utilisés par la Commission géologique du Canada pour évaluer le potentiel en hydrocarbures du bassin.

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UPPER CRETACEOUS TO PLEISTOCENE SEQUENCE STRATIGRAPHY OF THE BEAUFORT – MACKENZIE AND BANKS ISLAND AREAS, NORTHWEST CANADA

Abstract

Upper Cretaceous to Holocene sediments in the Beaufort – Mackenzie and Banks Island areas consist of clastic rocks deposited in deltaic, shelf, slope and deep water environments. At the basin margin, alternating sandstone- and shale-dominant successions that can be classified into discrete lithostratigraphic units are present. Basinward, however, the succession is predominantly shale, and conventional lithostratigraphic units can be less readily identified. Consequently, sequence analysis has been used to identify stratigraphic units within the basin fill. Stratigraphic and facies interpretation of reflection seismic, well, and, to a lesser extent, outcrop data form the main basis for the identification of the sequences, unconformities, maximum flooding surfaces, and internal depositional facies. Ages of the identified sequences have been determined mainly from benthic foraminiferal data and associated palynomorphs.

Eleven regionally extensive sequences have been identified. They are, from base to top, the Boundary Creek, Smoking Hills, Fish River, Aklak, Taglu, Richards, Kugmallit, Mackenzie Bay, Akpak, Iperk, and Shallow Bay. All the sequences are present in the Beaufort-Mackenzie area but only the Smoking Hills to Aklak, and the Iperk sequences are widespread in the Banks Island area. Major basin-margin delta complexes have been identified in the Fish River, Aklak, Taglu, Kugmallit, and Iperk sequences. A thin, remnant Richards Sequence delta complex is present locally in the Beaufort-Mackenzie Basin. Boundary Creek and Smoking Hills sequences are represented by outer shelf to possibly slope and basinal, organic-rich shale. Although thick shelf to basinal shales of the Mackenzie Bay and Akpak sequences are widespread in the Beaufort-Mackenzie Basin, no deltaic deposits have yet been identified. On Banks Island, the Miocene, nonmarine beds of the Beaufort Formation may be equivalent to either the Mackenzie Bay or Akpak sequences.

Although numerous workers attribute the origin of sequences to eustatic controls, many sequences in the Beaufort-Mackenzie Basin are associated with tectonic events originating in the Cordillera, and it is difficult, if not impossible, to separate the two influences. Comparison with published eustatic curves reveals that a lack of comparable and precise biostratigraphic data in the study area does not allow true comparisons to be made, only "best fit" comparisons, which are inaccurate tests of the synchroneity of events.

Résumé

Les sédiments du Crétacé supérieur à l'Holocène dans les régions de Beaufort-Mackenzie et de l'île Banks sont composés de roches clastiques déposées dans des milieux deltaïques, de plate-forme, de talus et de zones abyssales. En bordure du bassin, on trouve des successions alternantes principalement composées de grès et de schistes argileux qui peuvent être classifiées en unités lithostratigraphiques distinctes. Vers le bassin, cependant, la succession étant surtout composée de schistes argileux, il est plus difficile d'identifier les unités lithostratigraphiques classiques. C'est pourquoi l'analyse des séquences a été utilisée pour identifier les unités stratigraphiques au sein des sédiments de remplissage du bassin. Les interprétations de la stratigraphie et des faciès à partir de données de sismique réflexion et de puits et, dans une moindre mesure, des affleurements constituent la base principale de l'identification des séquences, des discordances, des surfaces de crue maximale et des faciès de sédimentation interne. Les datations des séquences identifiées ont été principalement faites à partir de données sur les foraminifères benthiques et les palynomorphes associés.

On a relevé onze séquences à l'échelle régionale. Ce sont, de la base au sommet, Boundary Creek, Smoking Hills, Fish River, Aklak, Taglu, Richards, Kugmallit, Mackenzie Bay, Akpak, Iperk et Shallow Bay. On trouve toutes ces séquences dans la région de Beaufort-Mackenzie mais seules celles de Smoking Hills à Aklak et celles d'Iperk sont largement présentes dans la région de l'île Banks. On a relevé d'importants complexes deltaïques de marge de bassin dans les séquences de Fish River, d'Aklak, de Taglu, de Kugmallit et d'Iperk. Un mince complexe deltaïque résiduel de la séquence de Richards est présent localement dans le bassin de Beaufort-Mackenzie. Les séquences de Boundary Creek et de Smoking Hills sont représentées par des schistes argileux riches en matières organiques dans une zone allant de plate-forme externe à probablement talus et bassin. Même si des schistes argileux épais de sédimentation en zone allant de plate-forme à bassin des séquences Mackenzie Bay et d'Akpak sont largement répandus dans le bassin de Beaufort-Mackenzie, on n'a toutefois pas encore trouvé de sédiments deltaïques. Sur l'île Banks, les couches non marines miocènes de la formation de Beaufort pourraient être équivalentes soit à la séquence de Mackenzie Bay ou à celle d'Akpak.

Même si de nombreux chercheurs attribuent l'origine des séquences à des phénomènes eustatiques, de nombreuses séquences du bassin de Beaufort-Mackenzie sont associées à des événements tectoniques prenant naissance dans la Cordillère, et il est difficile, sinon impossible, de séparer ces deux influences. Il ressort d'une comparison des courbes eustatiques publiées qu'on manque de données biostratigraphiques comparabels et précises de la zone à l'étude pour permettre des comparaisons réelles et que seules peuvent être faites des comparaisons "d'ajustement optimal", qui se révèlent etre des essais inexacts pour vérifier le synchronisme des événements.

Summary

The Beaufort Sea and adjacent land areas have been explored for hydrocarbons for over 20 years, and the Beaufort-Mackenzie area has substantial proven reserves and the potential for significant future discoveries. Also, the study area is proving to be a critical key to the unlocking of the geological history of Canada Basin. The scientific and economic need to produce a regional stratigraphic framework for the Beaufort Sea area resulted in this report, the product of many years of studying and re-evaluating data.

The study area extends from the Alaska–Yukon border eastward to Banks Island. Most of the study area underlies the Beaufort Sea. The continental shelf is 50 to 100 km wide and contains two recently formed channel-like features: the western Mackenzie Trough and an eastern channel extending from Amundsen Gulf. The water depth at the shelf edge varies from 60 m in the west to 500 m in the east, offshore Amundsen Gulf.

Albian and older strata form the structural basement on which Upper Cretaceous to Holocene strata underlying the Beaufort Sea and adjacent mainland were deposited. Two phases of sedimentation can be recognized in the Upper Cretaceous to Holocene succession of the mainland area. During the Cenomanian to Campanian, most of the sediments were trapped in foreland basins on the craton to the south of the Beaufort Sea and only a relatively thin succession of organic-rich muds was deposited in the Beaufort Sea area. The depositional area during this phase of sedimentation will be referred to in this report as the Porcupine–Mackenzie Basin. During the Maastrichtian, sedimentation shifted to the continental margin of the Beaufort Sea. The depositional basin for this younger phase of sedimentation will be referred to as the Beaufort–Mackenzie Basin. An estimated 12 to 16 km of predominantly Upper Cretaceous to Holocene strata underlie the central and eastern Beaufort shelf.

Early workers in the areas had limited access to reflection seismic data, or were limited by the confidentiality of the material; consequently, many of the early stratigraphic studies used conventional lithostratigraphic analysis. However, with the greater public access to reflection seismic data and increased drilling activity in the offshore areas, it became apparent that lithostratigraphic analysis had limited usefulness for basin-scale stratigraphic correlations. An alternative approach was to use depositional sequence analysis (Vail and Mitchum, 1977; Posamentier et al., 1988; Posamentier and Vail, 1988). However, some practical problems were encountered with the depositional sequence approach (Dixon and Dietrich, 1988) and that of the depositional sequence complex (Frazier, 1974), or its recently resurrected modified form, the genetic stratigraphic sequence (Galloway, 1988). Although these stratigraphic approaches have many advantages, we found some difficulties in applying the models to the Beaufort–Mackenzie and Banks Island successions. Consequently, we subdivided the succession into transgressive-regressive sequences. These approaches to genetic stratigraphy rely upon the recognition of different types of surfaces, the most important being unconformities and maximum flooding surfaces. These surfaces develop during relative changes in sea level and form the boundaries of sequences.

Using reflection seismic profiles as the principal data source, combined with data from exploration wells and limited outcrop data, eleven sequences were identified and dated in Upper Cretaceous to Holocene strata of the Beaufort-Mackenzie and Banks Island areas. In ascending order, these have been named the Boundary Creek Sequence (Cenomanian–Turonian), Smoking Hills Sequence (Santonian–Campanian), Fish River Sequence (Maastrichtian–Paleocene), Aklak Sequence (Paleocene), Taglu Sequence (Lower Eocene), Richards Sequence (Middle to Upper Eocene), Kugmallit Sequence (Oligocene), Mackenzie Bay Sequence (Oligocene–Miocene), Akpak Sequence (Miocene), Iperk Sequence (Pliocene–?lower Pleistocene), and Shallow Bay Sequence (?Pleistocene–Holocene). It has been our intent only to identify and name the large-scale, regionally extensive sequences. We realize that smaller scale sequences can be identified in many of the units, but the ability to trace these smaller scale sequences beyond local areas in the basin is

very limited. All of the identified sequences are present in the Beaufort–Mackenzie area, but because of extensive periods of erosion or nondeposition in the Banks Island area only the Smoking Hills, Fish River, Aklak and Iperk sequences are well represented, although there may be a thin erosional remnant of either the Mackenzie Bay or Akpak sequence on the island (Beaufort Formation).

Because sequences are not defined using lithological criteria they contain a range of depositional facies. Five of the eleven sequences in the Beaufort–Mackenzie and Banks Island areas are dominated by deltaic sediments; consequently, large delta complexes can be identified at the basin margins. Delta plain, delta front, prodelta/shelf, slope, submarine fan and basin plain depositional facies have been recognized from core, log shape, and seismic character. The thickest preserved deltaic strata occur in the Fish River, Aklak, Taglu, Kugmallit, and Iperk sequences. In the Richards, Mackenzie Bay and Akpak sequences, deltaic strata either are thin as a result of erosion, or have not been recognized with the available data. Submarine fan deposits have been recognized in the Fish River, Taglu, Kugmallit and Iperk sequences. The thickest and most widespread of the submarine fan successions is in the basal Kugmallit Sequence.

Two prominent unconformities separate Upper Cretaceous and Tertiary strata into tectonostratigraphic assemblages. A Middle Eocene unconformity, which separates Richards strata from older rocks, occurs at the top of a highly deformed succession. In the western Beaufort area, pre-Middle Eocene strata are deformed into anticlines, many of which are cut by north verging thrust faults. Middle Eocene to Upper Miocene strata are also deformed but less intensely than older beds. An Upper Miocene unconformity separates younger, essentially undeformed Plio–Pleistocene strata from older, more deformed strata.

Some workers (Vail et al., 1977; Haq et al., 1987) have attributed the origin of sequences solely to eustatic sea level changes and have produced coastal onlap and sea level curves that they believe represent global events. Comparison of the Beaufort–Mackenzie and Banks Island Upper Cretaceous to Holocene sequences with the onlap curves of the above authors is difficult because of the lack of biostratigraphic precision within the Beaufort succession when compared with the detailed curves and dating of Haq et al. (1987). Also, many of the unconformities identified in the Beaufort succession have a very strong tectonic component in their expression, and possibly their origin.

Sommaire

Pendant plus de vingt ans, la mer de Beaufor et les terres adjacentes ont fait l'objet de travaux d'exploration pétrolière. La région de Beaufort–Mackenzie recèle d'importantes réserves prouvées, et le potentiel de découvertes futures est élevé. En outre, cette région semble être d'une importance cruciale pour reconstituer l'histoire géologique du bassin Canada. Le besoin, à la fois scientifique et économique, de produire un cadre stratigraphique régional de la région de la mer de Beaufort est la raison d'être de ce rapport, résultat de nombreuses années d'étude et de réévaluation des données accumulées.

La région à l'étude s'étend de la frontière Alaska–Yukon jusqu'à l'île Banks, à l'est. La grande partie de la région se trouve sous la mer de Beaufort. La plate-forme continentale mesure entre 50 et 100 km de largeur et contient deux dépressions en forme de chenal de formation récente: l'ouest de la cuvette du Mackenzie et un chenal oriental prenant naissance dans le golfe Amundsen. La profondeur de l'eau à la bordure de la plate-forme continentale varie de 60 m à l'ouest à 500 m à l'est, au large du golfe Amundsen.

Les couches de l'Albien et plus anciennes forment le socle structural sur lequel se sont déposées les couches passant du Crétacé supérieur à l'Holocène reposant sous la mer de Beaufort et les terres continentales adjacentes. On peut distinguer deux phases de sédimentation dans la succession

continentale du Crétacé supérieur à l'Holocène. Durant la période allant du Cénomanien au Campanien, la plupart des sédiments on été piégés dans les bassins d'avant-pays, sur le craton au sud de la mer de Beaufort, et seule une succession relativement mince de boues riches en matières organiques s'est déposée dans la zone de la mer de Beaufort. La zone de sedimentation de cette phase sera appleée dans le present rapport le bassin Porcupine-Mackenzie. Durant le Maastrichtien, les sédiments se sont déplacés vers la marge continentale de la mer de Beaufort. Le bassin de sédimentation de cette phase plus récente sera appelé bassin de Beaufort-Mackenzie. Des couches surtout composées de sediments du Crétacé supérieur à l'Holocène, dont l'épaisseur est évaluée entre 12 et 16 km reposent sous les parties centrale et orientale de la plate-forme de Beaufort.

Les premiers chercheurs dans cette région avaient eu accès limité aux données de sismique réflexion ou étaient limités par le caractère confidentiel de leurs données; par conséquent, au cours des premières études stratigraphique, on a eu recours aux analyses lithostratigraphiques classiques. Cependant, depuis qu'il est plus facile d'avoir accès aux données de sismique réflexion et que les activités de forage ont augmenté dans les régions extracôtières, il est devenu évident que l'analyse lithostratigraphique était d'une utilitié limitée pour établir des corrélations stratigraphiques à l'échelle d'un bassin. Une autre méthode consistait à utiliser l'analyse des séquences sédimentaires (Vail et Mitchum, 1977; Posamentier et al., 1988; Posamentier et Vail, 1988). Toutefois, cette dernière méthode (Dixon et Dietrich, 1988) et celle liée au complexe sédimentaire (Frazier, 1974) ou sa forme modifiée reprise récemment, l'analyse de la séquence stratigraphique génétique (Galloway, 1988), ont soulevé certains problèmes pratiques. Même si ces méthodes stratigraphiques présentent de nombreux avantages, l'application des modèles aux successions de Beaufort-Mackenzie et de l'île Banks a créé des difficulés. La succession a donc été subdivisée en séquences transgressives-régressives. Ces façons d'aborder la stratigraphie génétique reposent sur différents types de surface, dont les plus importantes sont les discordances et les surfaces de crue maximale. Ces surfaces se forment durant les changements relatifs du niveau de la mer et constituent les limites des séquences.

En utilisant les profils de sismique réflexion comme principale source de données, combinés aux données provenant des puits d'exploration et aux donnees limitées sur les affleurements, on a identifié et daté onze séquences dans les couches passant du Crétacé supérieur à l'Holocène, des régions de Beaufort-Mackenzie et de l'île Banks. Par ordre ascendant, ces couches ont été désignées la séquence de Boundary Creek (Cénomanien-Turonien), la séquence de Smoking Hills (Santonien-Campanien), la séquence de Fish River (Maastrichtien-Paléocène), la séquence d'Aklak (Paléocène), la séquence de Taglu (Éocène inférieur), la séquence de Richards (Éocène de moyen à supérieur), la séquence de Kugmallit (Oligocène), la séquence de Mackenzie Bay (Oligocène-Miocène), la séquence d'Akpak (Miocène), la séquence d'Iperk (Pliocène-?Pléistocène inférieur) et la séquence de Shallow Bay (?Pléistocène-Holocène). Seules les séquences d'échelle régionale ont été identifiées et nommées. Les séquences de plus petite échelle auraient pu être identifiées dans de nombreuses unités mais la capacité de retracer ces séquences de petite échelle au-delà de certaines zones dans le bassin est très limitée. Toutes les séquences identifiées sont présentes dans la région de Beaufort-Mackenzie; cependant, comme la région de l'île Banks a été l'objet de périodes prolongées d'érosion et de non sédimentation, seules les séquences de Smoking Hills, de Fish River, d'Aklak et d'Iperk sont bien repésentées, mais il se pourrait qu'un reste d'érosion mince de la séquence de Mackenzie Bay ou d'Akpak subsiste dans l'île (formation de Beaufort).

Ces séquences n'étant pas définies selon des critères lithologiques, ils contiennent un éventail de faciès sédimentaires. Cinq des onze séquences des régions de Beaufort-Mackenzie et de l'île Banks sont principalement composées de sédiments deltaïques; par conséquent, on peut relever en bordure du bassin de grands complexes deltaïques. En se fondant sur les matériaux provenant de carottes, sur la forme des diagraphies et les caractéristiques des données sismiques, on peut distinguer des faciès de plaine deltaïque, de front deltaïque, de prodelta/plate-forme continentale, de talus, de cône sous-marin et de plaine de bassin. Les couches deltaïques conservées les plus épaisses se trouvent dans les séquences de Fish River, d'Aklak, de Taglu, de Kugmallit et d'Iperk. Dans les séquences de Richards, de Mackenzie Bay et d'Akpak, les couches deltaïques sont soit minces par suite de l'érosion, ou impossibles à distinguer avec les données disponibles. On a relevé des sédiments de cône sous-marin dans les séquences de fish River, de Taglu, de Kugmaillit et d'Iperk. La succession de cône sous-marin la plus épaisse et la plus vaste se trouve dans la séquence basale de Kugmallit.

Deux discordances importantes séparent les couches du Crétacé supérieur et Tertiaire en assemblages tectono-stratigraphiques. Une discordance de l'Éocène moyen, qui sépare les couches de la séquence de Richards de roches plus anciennes, s'observe au sommet d'une succession très déformée. Dans l'ouest de la région de Beaufort, des couches antérieures à l'Éocène moyen sont déformées en anticlinaux, dont plusieurs sont recoupées par des failles chevauchantes à vergence nord. Les couches de l'Éocène moyen au Miocène supérieur sont également déformées mais moins intensément que les couches plus anciennes. Une discordance du Miocène supérieur sépare les couches plio-pléistocènes plus récentes et essentiellement non déformées des couches plus anciennes davantage déformées.

Certains chercheurs (Vail et al., 1977; Haq et al., 1987) ont attribué l'origine des séquences aux seuls changements d'origine eustatique du niveau de la mer et ont tracé des courbes du biseau d'aggradation littoral et du niveau de la mer qu'ils croient représenter des événements globaux. Il est difficile de comparer les séquences passant du Crétacé supérieur à l'Holocène des régions de Beaufort-Mackenzie et de l'île Banks avec les courbes du biseau d'aggradation des chercheurs susmentionnes à cause du manque de précision biostratigraphique de la succession de Beaufort lorsqu'on la compare avec les courbes et les datations détaillées de Haq et al. (1987). En outre, de nombreuses discordances dans la succession de Beaufort présentent une très forte composante tectonique dans leur manifestation et probablement dans leur origine.

INTRODUCTION

The Beaufort Sea and adjacent land areas hold proven reserves of oil and gas, and there is the potential for significant future discoveries. Consequently, this area of northwest Canada probably will be a major producer of hydrocarbons in the 21st century. In order to better evaluate the geology and economic potential of the area, a basin-wide stratigraphic framework is a primary objective. This report sets out to attain this objective by identifying and describing basin-wide stratigraphic units, which we hope will provide the basis for more refined geological analysis.

Acknowledgments

This study is the result of many years of work during which the authors have had the opportunity to discuss the results and methodology with numerous individuals from the petroleum industry, other government agencies and university personnel. To these many, anonymous individuals we offer our thanks. A long-term study such as ours required the help and support of many of the technical and administrative staff within the Institute of Sedimentary and Petroleum Geology to whom we are very grateful. To A.F. Embry we would like to offer our sincerest thanks for the many years of stimulating and fruitful discussion regarding sequence concepts and their practical application. Critical comments by B.C. Maclean, G.R. Morrell and A.F. Embry on an original draft version helped to improve the text. P. Wolter did the drafting with additional help from the ISPG Cartographic Unit.

Geographic setting

The study area extends northward from latitude 68°N to the Beaufort Sea continental slope, and from Banks Island westward to 141°W. Some information from the Alaskan part of the Beaufort Sea is included in the study (Fig. 1, in pocket).

The Beaufort Sea is bounded on its landward margin by the coastal plain of Banks Island, the Northwest Territories mainland, and the Yukon, with Banks Island separated from the mainland by Amundsen Gulf (Fig. 2). On Banks Island the coastal plain rises to a low-lying plateau of the Victoria Lowlands. On the mainland, the Mackenzie River and its delta separate two distinct physiographic areas. East of the delta are the lowlands of Anderson Plain and to the west are the Richardson and British mountains (Fig. 2). South of the British Mountains are the lowlands of Old Crow Plain.

The continental margin beneath the Beaufort Sea can be divided into a number of physiographic areas. The shallow water shelf is 50 to 100 km wide and is characterized by low, uniform slope gradients of 1 to 2 m/km. Two major, channel-like features extend across the shelf. In the west Beaufort, east and northeast of Herschel Island, is the Mackenzie Trough (formerly Mackenzie Canyon), a northwest trending depression 100 to 500 m deep. Extending across the shelf from Amundsen Gulf is another trough of similar depth. The two troughs are geologically recent erosional features. Slope gradients change to 5 to 30 m/km at the shelf edge, seaward of which is the 50 to 100 km wide continental slope. Water depth at the shelf edge varies from 60 m in the west to almost 500 m northwest of Amundsen Gulf.

In the vicinity of Mackenzie Trough, the continental slope comprises upper and lower portions. The upper slope has gradients of 5 to 70 m/km and extends to water depths of 500 to 800 m. Grantz et al. (1981) referred to the upper slope as the Beaufort Ramp in Alaskan waters. Gradients up to 170 m/km are present on the lower slope. The lower slope merges with the continental rise in water depths of 1500 to 2000 m. Gradients of 10 to 15 m/km are typical of the continental rise. The continental rise extends for several hundred kilometres into Canada Basin.

Previous work

Much of the early detailed geological work on Upper Cretaceous to Pleistocene strata in the Beaufort-Mackenzie area began with the mapping of Norris (1981a-d), who began the work under the Geological Survey of Canada's Operation Porcupine program in 1962, and the stratigraphic studies of Mountjoy (1967), Chamney (1969, 1973), Jeletzky (1960, 1972), Holmes and Oliver (1973), Young (1973, 1975) and Young et al. (1976). These studies were mostly of outcrops in the northern Yukon, although some subsurface studies were undertaken. With the increase in drilling activity and in the acquisition of reflection seismic data in pursuit of hydrocarbons during the 1970s, the emphasis in geological work switched to the subsurface, where the bulk of Upper Cretaceous to Pleistocene strata are found. Some of the earlier regional work incorporating subsurface studies includes that of Hofer and Varga (1972), Lerand (1973), Sirrine (1973), Yorath (1973), Hawkings and Hatlelid (1975), and Young et al. (1976). Detailed local studies also began to appear, such as, Bowerman and Coffman (1975), Myhr (1975), Dixon and Snowdon (1979), Price et al. (1980), Jones et al. (1980), Dixon (1981), McNeil et al. (1982), Nentwich and Yole (1982), Dixon et al. (1984), and Dietrich et al. (1989).

Stratigraphic nomenclature in the Beaufort-Mackenzie area has been published by Willumsen and Cote (1982), Young and McNeil (1984), and Dietrich et al. (1985). A conventional lithostratigraphic approach was used by Young and McNeil (1984) for Tertiary strata underlying Mackenzie Delta, whereas Dietrich et al. (1985) preferred the seismic/depositional sequence approach, which could be applied to the whole basin. Dixon et al. (1985) produced a summary of stratigraphy, biostratigraphy and organic geochemistry of strata in the basin. Recent stratigraphic/structural syntheses include those of Hea et al. (1980), Norris and Yorath (1981), Balkwill et al. (1983), Dixon (1986, in press a), and Gardner and Bates (1987). Regional studies of Pleistocene-Holocene strata have been written by Mackay (1963), Fyles (1966, 1967), Rampton (1969), Hughes (1972), and Vilks et al. (1979). A special folio-size volume on Recent sediments of the Beaufort shelf was compiled by Bornhold et al. (1984). A similar, folio-size publication dealing with geology and geophysics was edited by Pelletier (1987).

Comprehensive geological studies on Banks Island began with Thorsteinsson and Tozer (1962) and continued with the work of Miall (1975, 1976, 1979) and Plauchut and Jutard (1976). These studies were land based; very little has been written about the offshore (Lerand, 1973; Miall, 1975, 1979), primarily because of the lack of data.

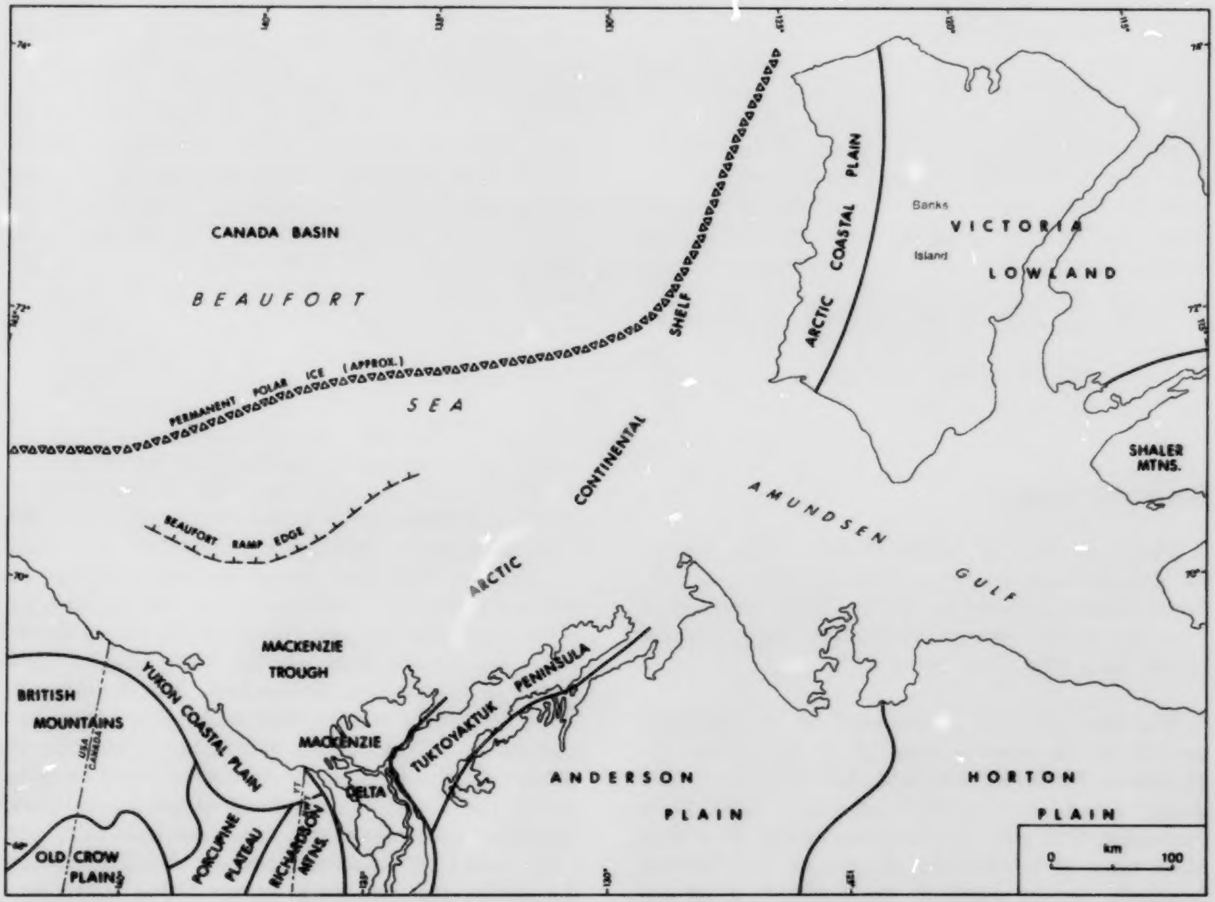

CANADA BASIN
BEAUFORT
SEA
PERMANENT POLAR ICE (APPROX.)
SHELF
CONTINENTAL
ARCTIC
BEAUFORT RAMP EDGE
ARCTIC COASTAL PLAIN
Banks Island
VICTORIA LOWLAND
SHALER MTNS.
AMUNDSEN GULF
MACKENZIE TROUGH
BRITISH MOUNTAINS
USA CANADA
YUKON COASTAL PLAIN
MACKENZIE DELTA
TUKTOYAKTUK PENINSULA
ANDERSON PLAIN
HORTON PLAIN
OLD CROW PLAINS
PORCUPINE PLATEAU
RICHARDSON MTNS
0 km 100
74°
72°
70°

Figure 2. Physiographic elements.

Current study

The present study documents and interprets Upper Cretaceous to Holocene stratigraphy in the Beaufort-Mackenzie and offshore Banks Island areas. The database includes 260 wells (Fig. 1) and approximately 100 000 km of released reflection seismic data. Most of the wells penetrated Upper Cretaceous and/or Tertiary strata. Stratigraphic divisions are based on the recognition of regionally extensive transgressive-regressive sequences. Well cuttings and cores from many of the wells have been examined, although for most wells the gross lithological character is ably documented by commercially available lithology logs produced by Canadian Stratigraphic Service Ltd. of Calgary. Cores and cuttings are available for viewing at the Geological Survey of Canada, Institute of Sedimentary and Petroleum Geology, Calgary. Nonconfidential reflection seismic data can be viewed or obtained from the offices of the National Energy Board, Calgary.

Structural setting

The landward side of the continental margin contains a variety of tectonic elements (Fig. 3; Norris, 1972; Miall, 1974). Banks Island is flanked by and underlain by Paleozoic strata of the Prince Albert Homocline. Proterozoic strata outcrop at the southern end of Banks Island in the Cape Lambton Uplift. Between Paleozoic and Upper Cretaceous strata are Jurassic and Lower Cretaceous rocks preserved in grabens and half-grabens (Miall, 1974, 1979), separated by local uplifts.

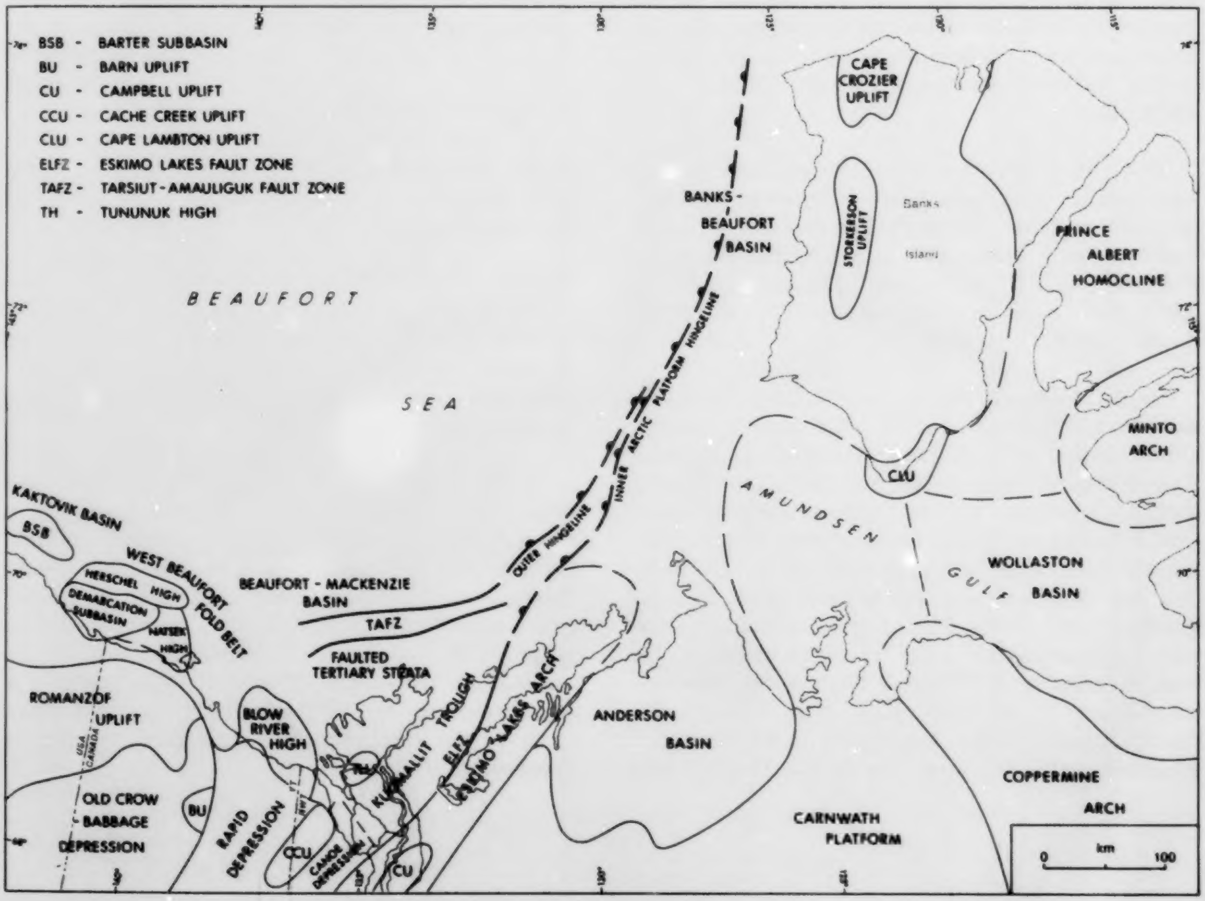

BSB - BARTER SUBBASIN
BU - BARN UPLIFT
CU - CAMPBELL UPLIFT
CCU - CACHE CREEK UPLIFT
CLU - CAPE LAMBTON UPLIFT
ELFZ - ESKIMO LAKES FAULT ZONE
TAFZ - TARSIUT-AMAULIGUK FAULT ZONE
TH - TUNUNUK HIGH
BEAUFORT
SEA
CAPE CROZIER UPLIFT
STORKERSON UPLIFT
Banks Island
BANKS-BEAUFORT BASIN
PRINCE ALBERT HOMOCLINE
MINTO ARCH
INNER ARCTIC PLATFORM HINGELINE
OUTER HINGELINE
CLU
AMUNDSEN GULF
WOLLASTON BASIN
KAKTOVIK BASIN
BSB
WEST BEAUFORT FOLD BELT
HERSCHEL HIGH
DEMARCATION SUBBASIN
HATSEK HIGH
BEAUFORT-MACKENZIE BASIN
TAFZ
FAULTED TERTIARY STRATA
ROMANZOF UPLIFT
USA
CANADA
BLOW RIVER HIGH
KUGMALLIT TROUGH
ELFZ
ESKIMO LAKES ARCH
TH
ANDERSON BASIN
OLD CROW - BABBAGE DEPRESSION
BU
RAPID DEPRESSION
CCU
CANOE DEPRESSION
CU
CARNWATH PLATFORM
COPPERMINE ARCH
0 km 100
140°
135°
130°
125°
120°
115°
74°
72°
70°

Figure 3. Tectonic elements. (Modified from Norris, 1972; Miall, 1979; Yorath and Cook, 1981; Dixon et al., 1985.)

On the southeast flank of Beaufort-Mackenzie Basin is the Eskimo Lakes Arch (Fig. 3; Young et al., 1976; the Eskimo Lakes Arch is the northeasternmost element of the Aklavik Arch Complex), which is bounded on its northwestern side by normal faults of the Eskimo Lakes Fault Zone (Cote et al., 1975; Young et al., 1976; the fault zone was originally called the Tuktoyaktuk Fault Flexure Zone by Lerand, 1973). Yorath (1973) used the term Kugaluk Arch for what is more commonly known as the Eskimo Lakes Arch. Young et al. (1976) had originally intended the Eskimo Lakes Arch to be a Columbian (Jurassic–Early Cretaceous) tectonic element and the Eskimo Lake Fault Zone as its Laramide (Late Cretaceous-Early Tertiary) expression. However, common usage has not kept these intended nuances and the arch and fault zone refer to their present-day expression as a structurally high area and its northwest bounding faults, respectively. The arch contains a thin Mesozoic–Cenozoic cover and a thick lower Paleozoic and Proterozoic succession, the latter outcropping in Campbell Lake Uplift (Fig. 3). Deep-reflection seismic data across the Eskimo Lakes Fault Zone show that the faults are listric, soling-out at considerable depths within presumed Proterozoic strata (Cook et al., 1987a, b).

East and southeast of the Eskimo Lakes Arch is Anderson Basin, containing a thin veneer of Mesozoic sediment underlain by a thick succession of lower Paleozoic and Proterozoic strata of the Carnwath Platform (Fig. 3). The Carnwath Platform and Prince Albert Homocline have been grouped as part of the Arctic Platform (Dixon and Dietrich, 1990).

On the northwest side of Eskimo Lakes Arch is a structural depression known as Kugmallit Trough (Young et al., 1976). Although principally a Jurassic–Early Cretaceous half-graben, it continued to influence Tertiary deposition through differential subsidence. Under Mackenzie Delta, the northwest flank of the trough rises into Tununuk High (Lerand, 1973). Tununuk High was originally defined on the basis of gravity expression, but Dixon (1982) showed that some Lower Cretaceous units thin or are truncated on the high. Southwest of Tununuk High is the Permian-cored Cache Creek Uplift (Figs. 1, 3). Young et al. (1976) considered the Tununuk and Cache Creek structures to be the same feature but Dixon (1982) noted that there is a structural depression separating them, within which there is a more complete Mesozoic succession.

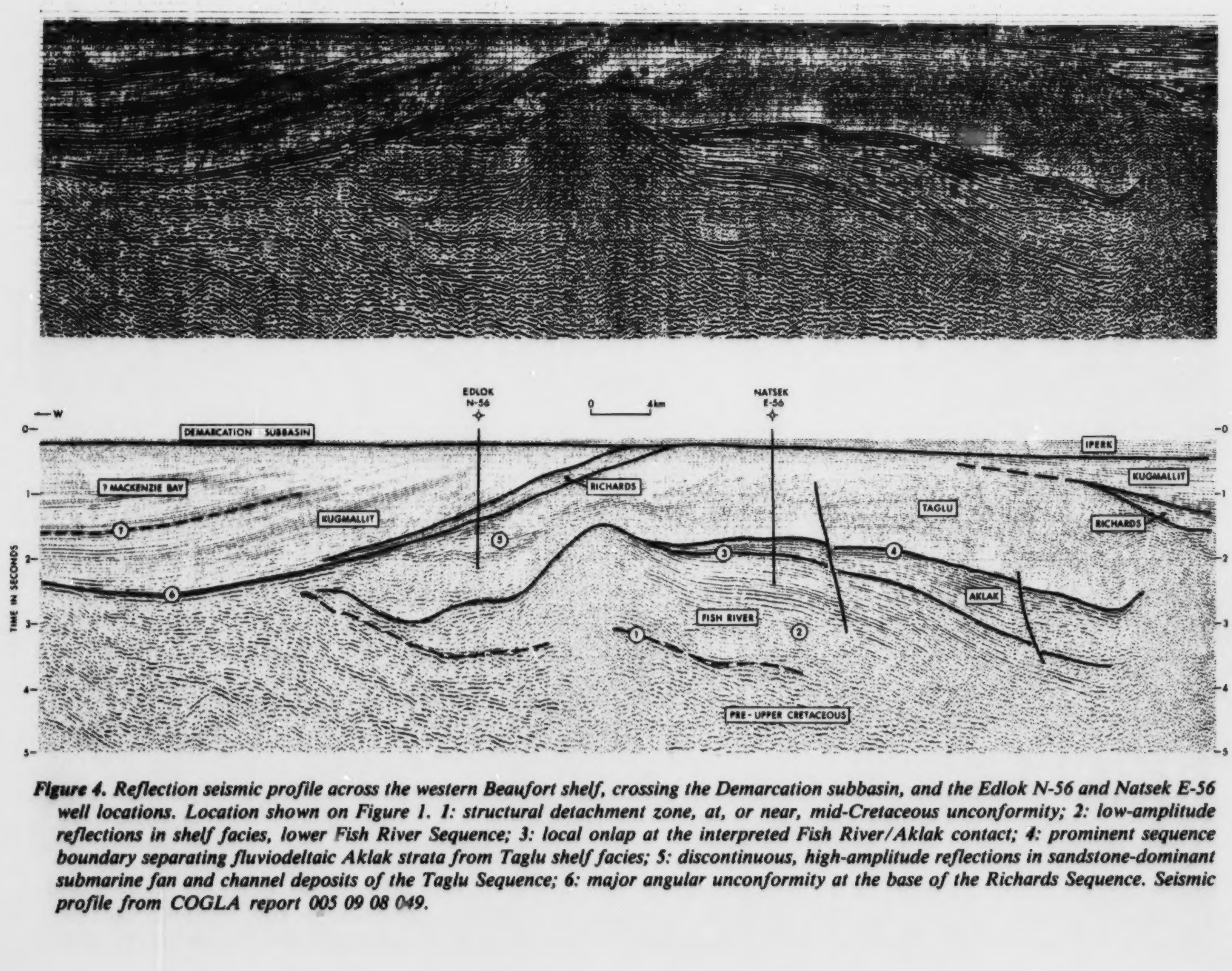
At the southern end of Caribou Hills, on the east side of Mackenzie Delta, Middle and Upper Paleocene strata rest erosionally on Santonian–Campanian strata. This local early Tertiary erosional feature has been identified as the Caribou High by Young et al. (1976, Fig. 3).

West of Cache Creek Uplift there is a structural low known by at least two names — the Rapid Depression (Norris, 1972) or Blow Trough (Young et al., 1976) — although the latter term was intended only to refer to its Columbian (Jurassic–Early Cretaceous) expression. The Rapid Depression contains a thick Jurassic to Albian fill and is cut by numerous faults of the Rapid Fault Array (Yorath and Norris, 1975), which some authors later referred to as the Kaltag–Rapid Fault Array (Young et al., 1976). Lane (1988), however, noted that the Rapid Depression also contains many prominent folds and that many of the faults are not as prominent as originally mapped.

West of the Rapid Depression is the Paleozoic-cored Barn Uplift (Fig. 3), and northwest of that is the larger, Romanzof Uplift (Fig. 3). The two uplifts are separated by a northerly extension of the Old Crow–Babbage Depression.

Most of the land-based tectonic elements have their origins at least as Mesozoic features, and many may have much older precursor elements. Their present expression is mostly the result of Jurassic and Early Cretaceous tectonic activity with rejuvenation and modification in Tertiary time.

Under the central and western Beaufort shelf and slope the Upper Cretaceous to Holocene succession is the only clearly imaged section on reflection seismic profiles (Figs. 4-6). However, in the eastern Beaufort, Tuktoyaktuk Peninsula and the adjacent nearshore, and under Banks Island and its nearshore areas (Figs. 7, 8), pre-Upper Cretaceous strata can be imaged. The pre-Upper Cretaceous surface acts as a structural basement for overlying rocks, and in some parts of the Beaufort–Mackenzie Basin acts as a decollement surface (Fig. 4).


— W
EDLOK
N-56
0
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NATSEK
E-56
DEMARCATION SUBBASIN
IPERK
KUGMALLIT
? MACKENZIE BAY
RICHARDS
TAGLU
KUGMALLIT
RICHARDS
AKLAK
FISH RIVER
PRE-UPPER CRETACEOUS
1
2
3
4
5
6
TIME IN SECONDS
0
1
2
3
4
5

Figure 4. *Reflection seismic profile across the western Beaufort shelf, crossing the Demarcation subbasin, and the Edlok N-56 and Natsek E-56 well locations. Location shown on Figure 1. 1: structural detachment zone, at, or near, mid-Cretaceous unconformity; 2: low-amplitude reflections in shelf facies, lower Fish River Sequence; 3: local onlap at the interpreted Fish River/Aklak contact; 4: prominent sequence boundary separating fluviodeltaic Aklak strata from Taglu shelf facies; 5: discontinuous, high-amplitude reflections in sandstone-dominant submarine fan and channel deposits of the Taglu Sequence; 6: major angular unconformity at the base of the Richards Sequence. Seismic profile from COGLA report 005 09 08 049.*

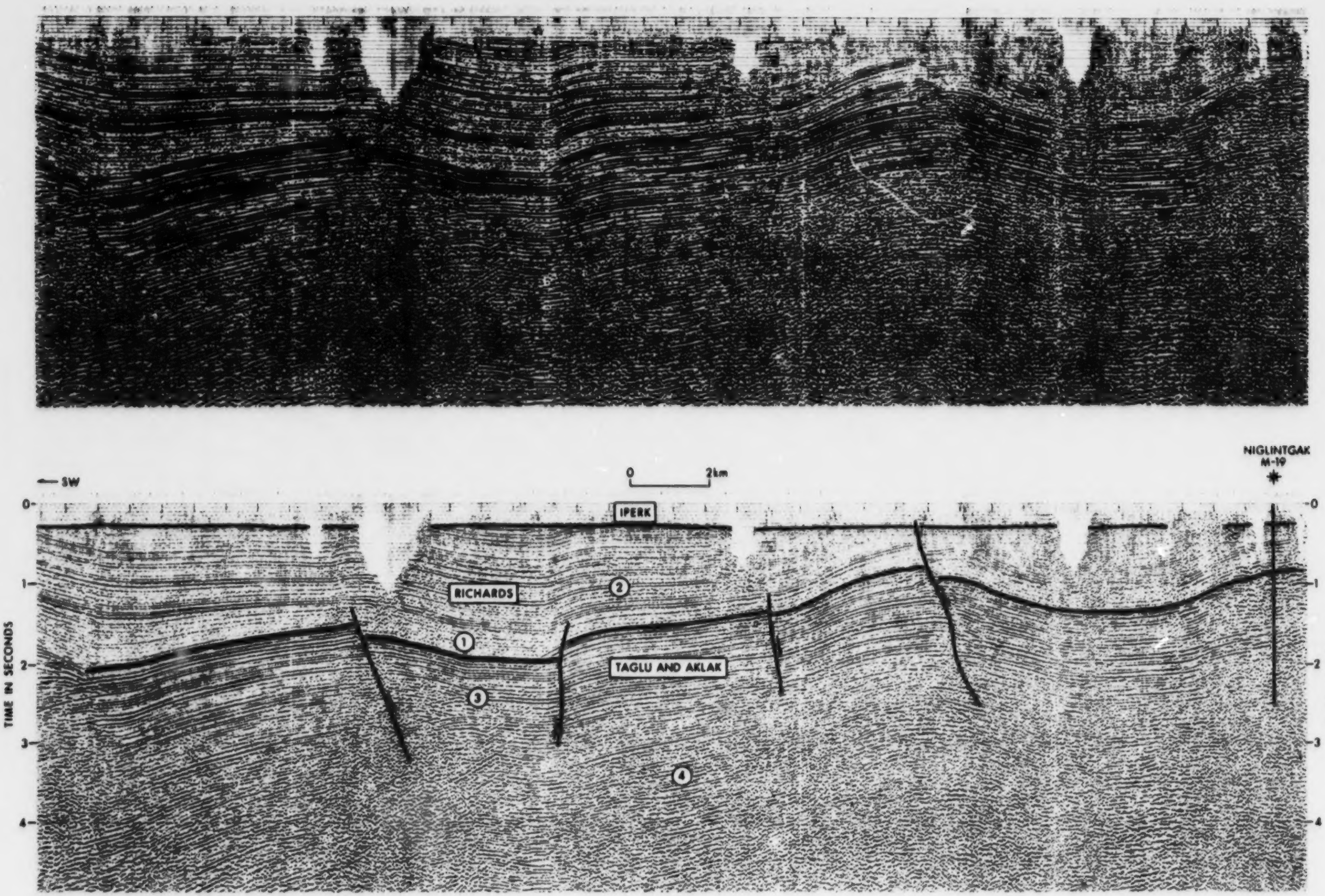


Figure 5. Reflection seismic profile across western Richards Island, Mackenzie Delta. Location shown on Figure 1. 1: low-amplitude reflections in outer shelf facies of the lower Richards Sequence; 2: moderate to high-amplitude reflections in prodelta/shelf facies of the upper Richards Sequence; 3: high-amplitude reflections in fluviodeltaic strata of the Aklak and Taglu sequences; 4: low-amplitude, discontinuous reflections in (?)shelf strata of the Fish River and lower Aklak sequences. Seismic profile from COGLA report 025 06 07 027.

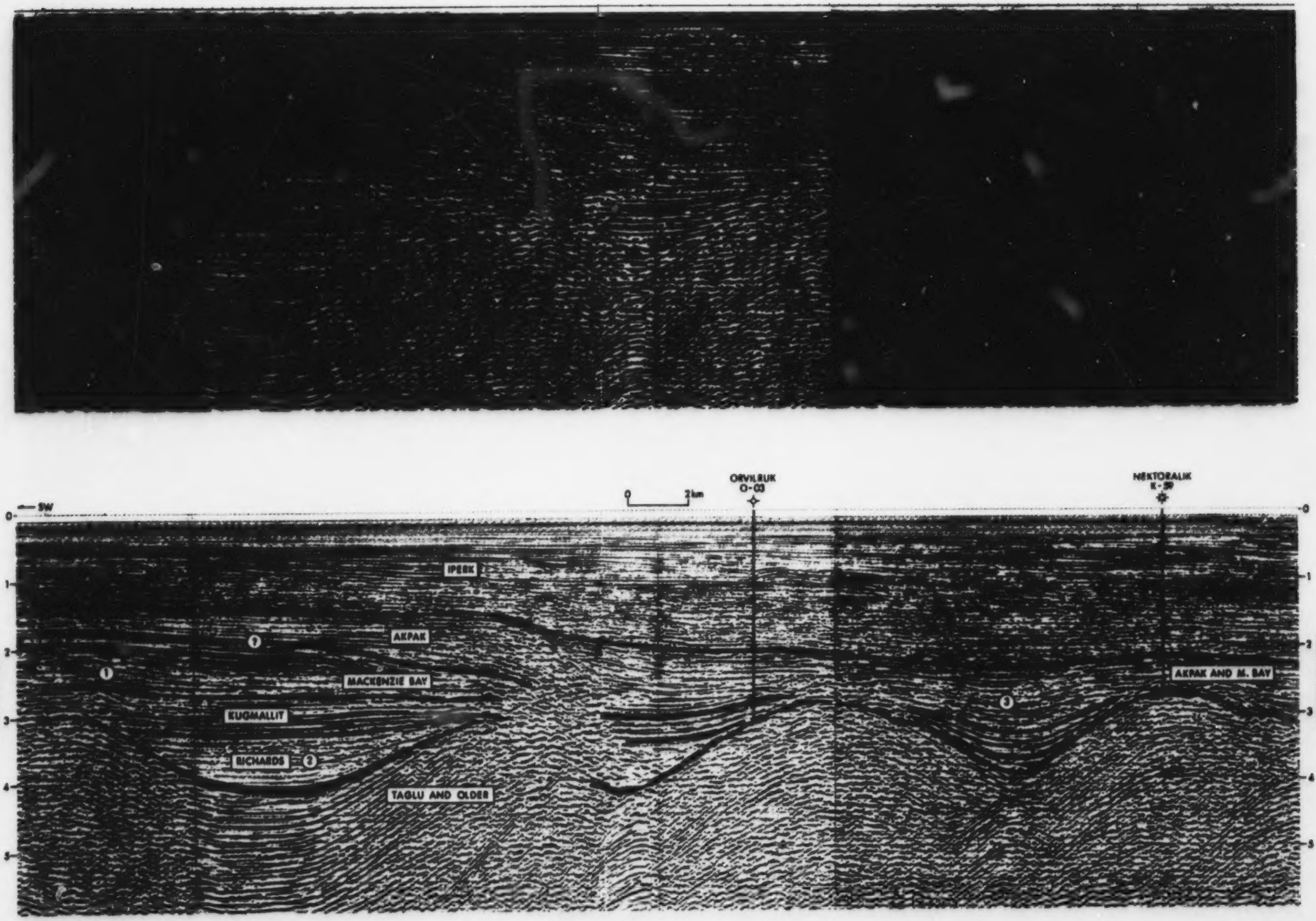


Figure 6. Reflection seismic profile across the northwest Beaufort shelf. Location shown on Figure 1. 1: intrasequence downlap of continental slope clinoforms; 2: low-amplitude reflections in (?)basinal Richards strata; 3: subparallel bottomset reflections in deep water, basin plain strata of the Kugmallit, Mackenzie Bay, and Akpak sequences. Seismic profile from COGLA report 025 09 08 030.

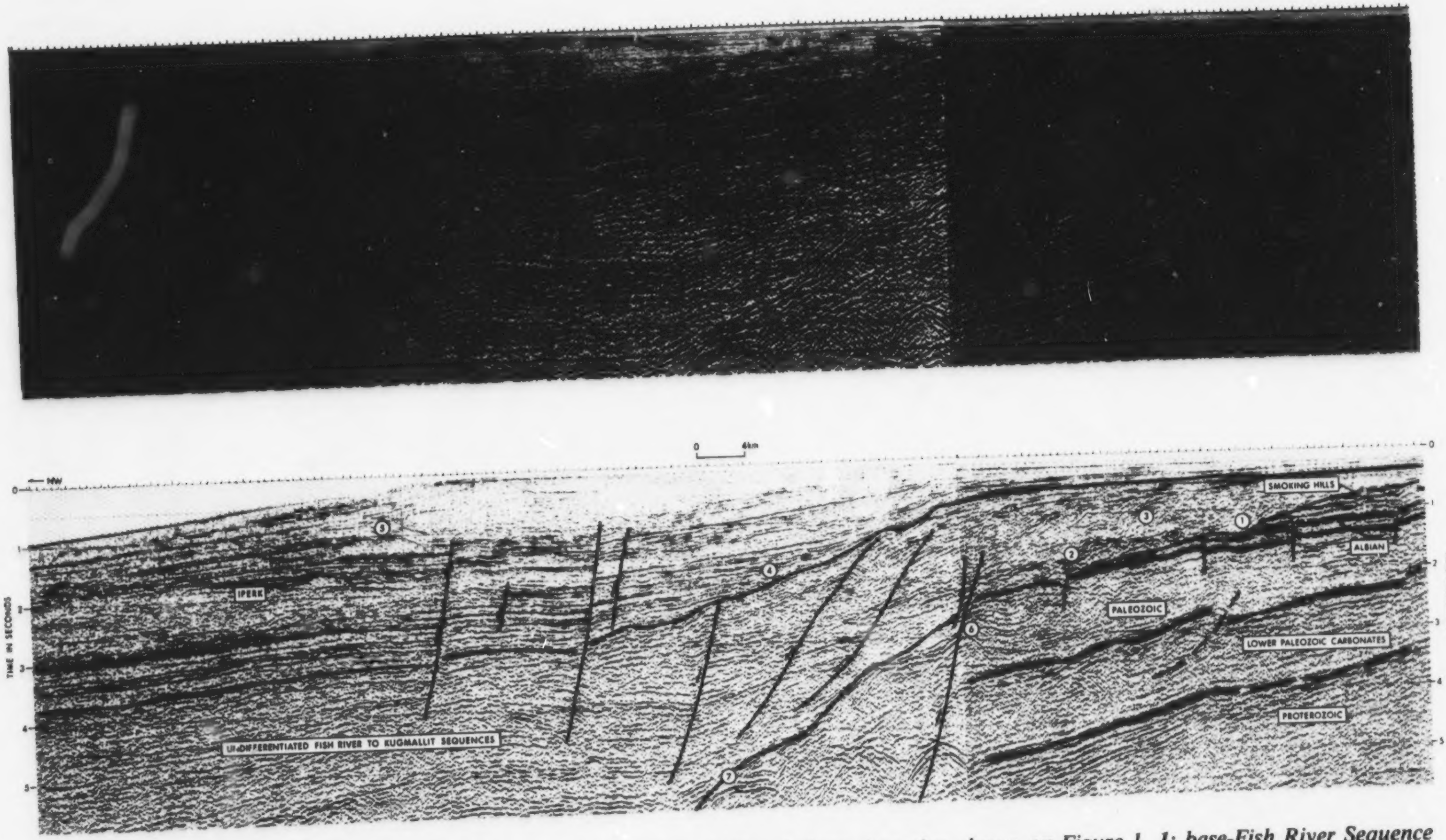


Figure 7. *Reflection seismic profile across the northeast Beaufort shelf and slope. Location shown on Figure 1. 1: base-Fish River Sequence unconformity; 2: hummocky discontinuous reflections in Fish River Sequence (?submarine fan deposits); 3: prograding continental slope clinoforms in Fish River and Aklak sequences; 4: marine onlap of Iperk strata onto a Late Miocene unconformity; 5: continental slope slide-blocks in the Iperk Sequence; 6: Eskimo Lakes Fault Zone (Arctic Platform Hinge Line); 7: Outer hinge line. Geological Survey of Canada seismic profile 87-1 (Cook et al., 1987a).*

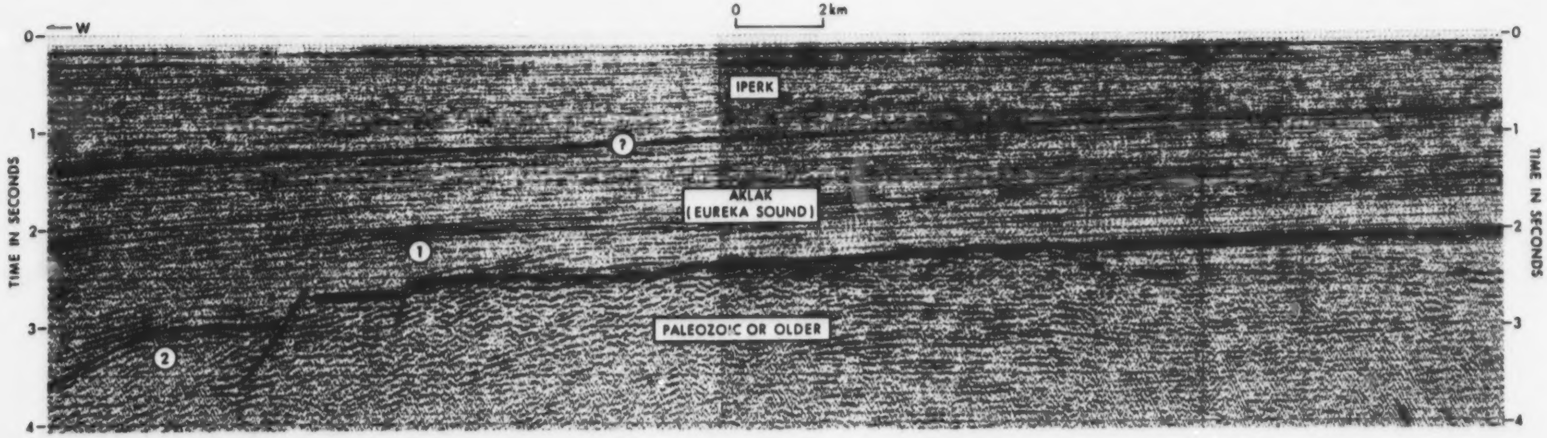


Figure 8. Reflection seismic profile offshore Banks Island. Location shown on Figure 1. 1: low-angle clinoforms in Aklak Sequence; 2: Arctic Platform Hinge Line. Seismic profile from COGLA report 528 09 08 016.

West of Herschel Island, Eocene to Miocene strata occur in a large synclinal structure, known as the Demarcation subbasin (Figs. 3, 4), also called the Jago Basin by Hea et al. (1980). The northern flank of the subbasin is bounded by the Herschel High (Fig. 3); Hea et al. (1980) originally referred to it as an arch. Southeast of Herschel High is the Blow River High (Fig. 3), first named by Hea et al. (1980). Both the Herschel and Blow River highs have a similar structural expression, consisting of very closely spaced anticlines in Upper Cretaceous to Eocene strata. Hea et al. (op. cit.) felt that Jurassic to Tertiary strata were involved in the Blow River structure. However, reflection seismic data at the southeast end of the Blow River High show that Upper Cretaceous and Tertiary strata are folded and detached above older rocks. The studies of Lane (1988) in the Rapid Depression to the south of Blow River High, indicate that complex folds are present in Albian strata. This suggests that older strata under Blow River High also are complexly folded. In the western part of the Beaufort-Mackenzie Basin, north of the Herschel and Blow River highs, the Upper Cretaceous to Eocene section is folded into an arcuate array of anticlines. In the more landward part of the foldbelt the anticlines have a distinct asymmetry, with the steeper limbs facing oceanward, and are interpreted as being cut by thrust faults (Fig. 9). The folds become progressively more symmetrical and less faulted in a seaward direction.

In the central Beaufort-Mackenzie Basin, large-scale listric faults are the dominant structures (Fig. 10). Between Tarsiut and Ukalerk there are a series of large listric faults, many of which can be traced for long distances, and which have been referred to as the Tarsiut-Amauligak Fault Zone (Fig. 3; Morrell and Schmidt, 1988). The faults have large normal displacements with both north-side and south-side down offsets, although most of the latter faults are restricted to the western end of the fault zone. The faults are oriented in east-west to southwest-northeast trends, and at the western end of the zone, obliquely intersect the north to northwesterly trending anticlines of the west Beaufort foldbelt. A second prominent Tertiary fault zone occurs onshore, beneath Richards Island. This array of northeast- and east-trending normal faults are herein referred to as the Taglu Fault Zone.

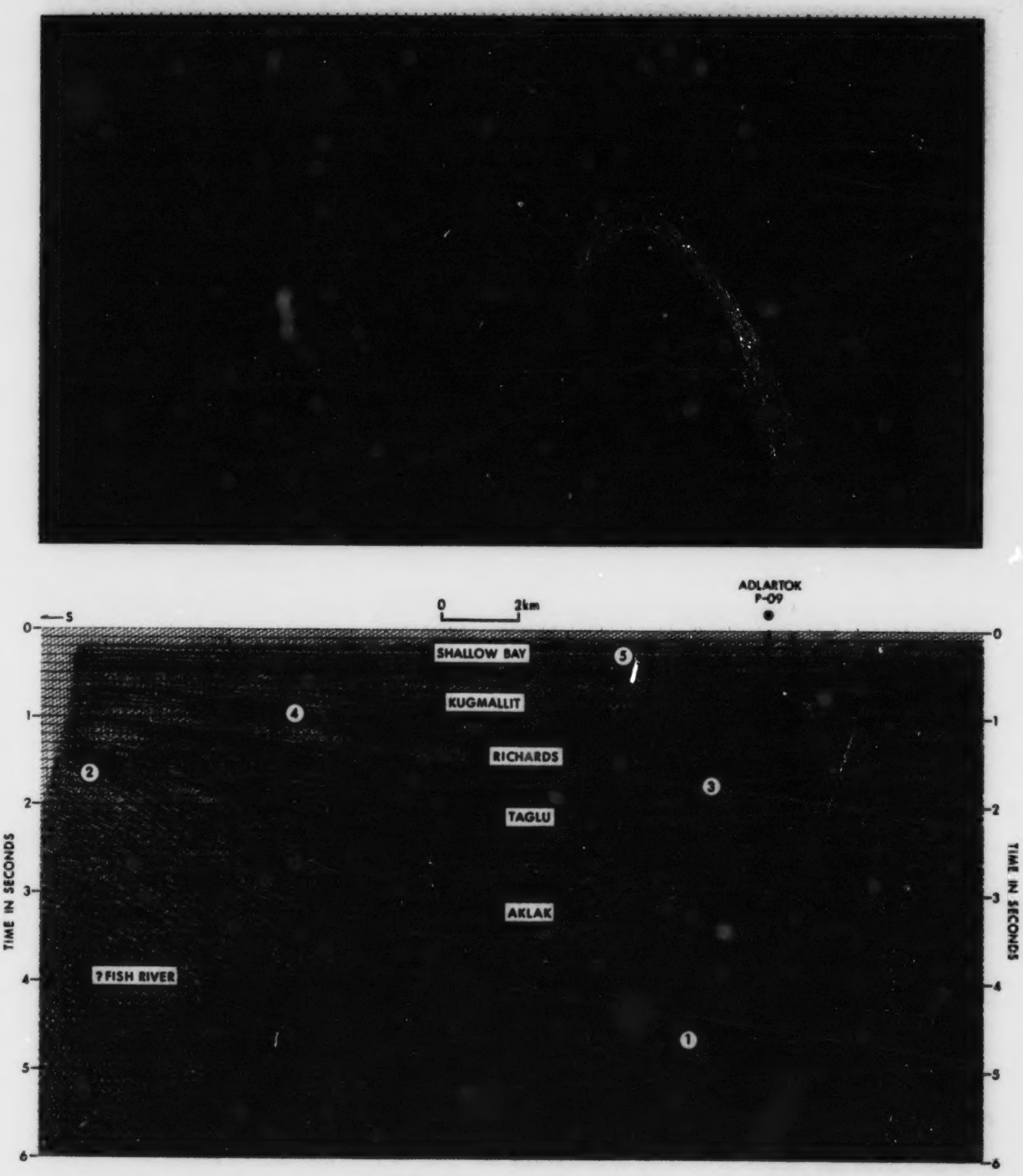
The prominent folds and faults that characterize the western and central Beaufort are absent in the eastern Beaufort and Banks Island areas, where the Upper Cretaceous-Tertiary strata are essentially undeformed (Figs. 7, 8). However, there are two prominent northeast trending hinge lines and associated faults across which the succession rapidly thickens (Figs. 3, 7). The inner hinge line is an extension of the Eskimo Lakes Fault Zone and has been called the Arctic Platform Hinge Line (Dixon et al., 1985, Fig. 2). Seaward of the inner hinge line is a second, outer hinge line or faulted basement margin (Fig. 7). The south end of the outer hinge line may extend southwest beneath Richards Island, into the Taglu Fault Zone.

BASIN DEFINITIONS

A considerable number of basin names have been used in the study area and it is necessary to discuss their original definitions, past usage, and those adopted for this report (Figs. 3, 11). The underlying objective in the following discussion is to identify and distinguish between depositional basins and structural/preservational basins. The latter are features identified by their present geographic, structural and stratigraphic expression; the former are paleogeographic features identified on the bases of facies trends, sediment thicknesses and, to some extent, interpretation of regional tectonic elements during deposition. Structural/preservational and depositional basins may be coincidental during some phases of development but that is not always the case. In the following discussion, the large-scale basins that have been identified for this report will be defined on the bases of stratigraphic, geographic and tectonic constraints, and will be close approximations to depositional basins. The large-scale basins are characterized by common paleogeographic settings, similar depositional facies and similar tectonic histories. The span of time during which the basins existed varies, and the beginning and end of a developing basin may overlap its predecessor or successor.

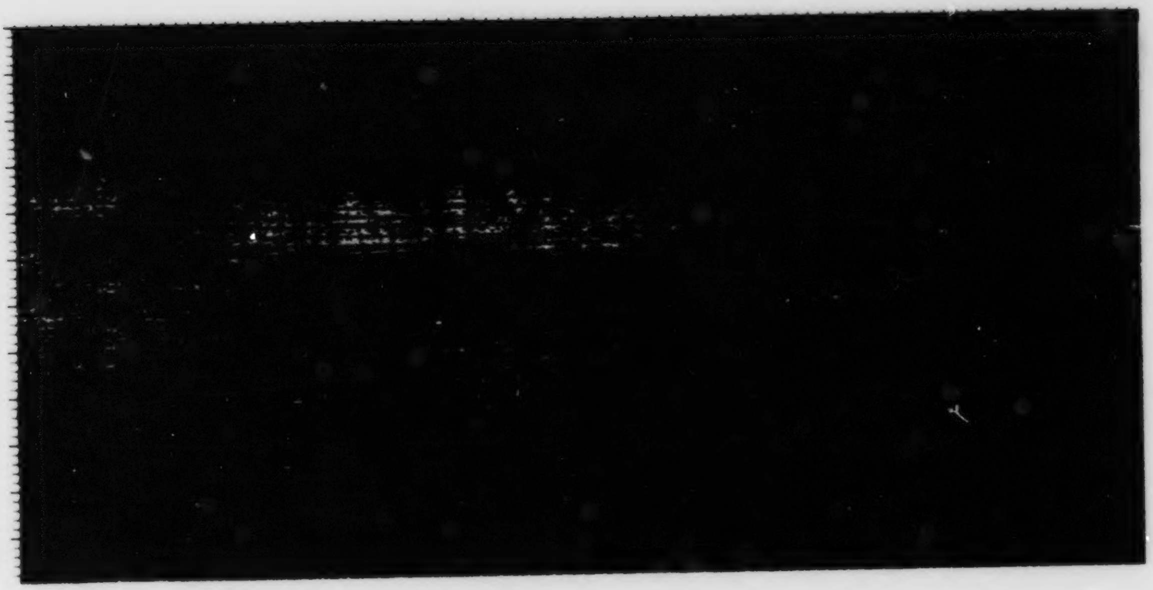
Mainland Canada and Beaufort Sea areas

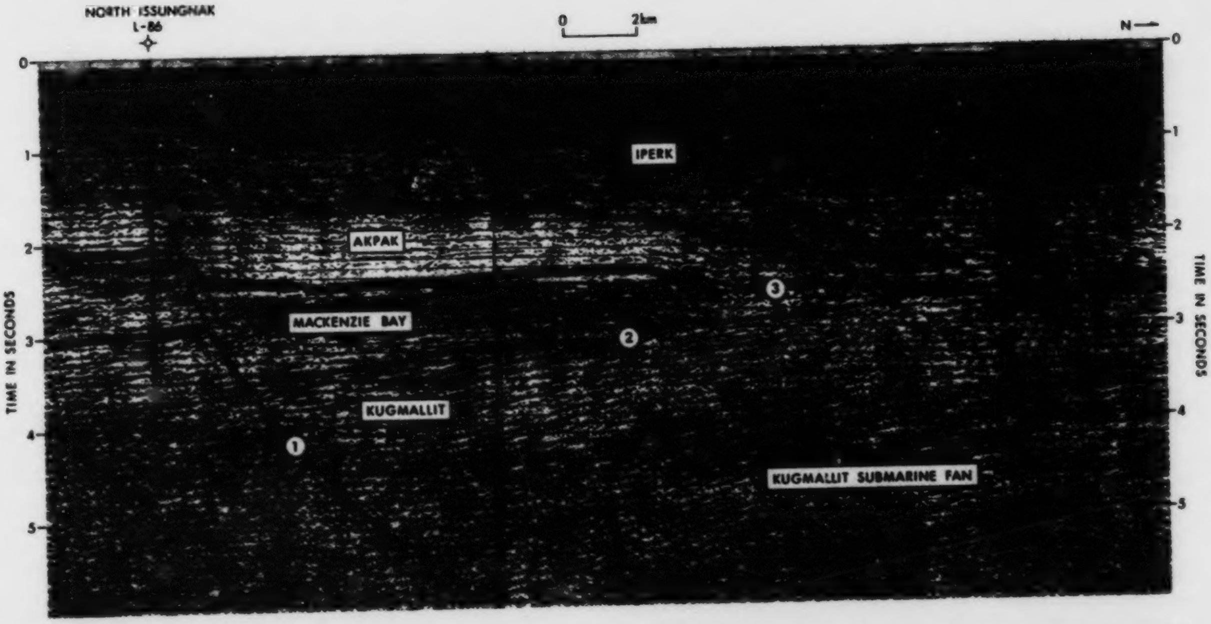
Lerand (1973) coined the term "Mackenzie Basin" and defined it as ". . . a sedimentary depocentre surrounded by the Romanzof Uplift, the northern Richardson Mountains, the Aklavik Arch, the continental shelf off Banks Island and the continental shelf off northern Alaska . . .". He continued, "In a general sense, the southern boundary is marked by the zero edge of the Tertiary sediments. . . ." (op. cit., p. 323-326). Although the latter seems to imply some stratigraphic limits, the remainder of the text leaves no doubt that all Mesozoic and Cenozoic strata are part of the basin fill. In effect the Mackenzie Basin is partly a preservational basin and partly a stratigraphically limited depositional basin.



ADLARTOK
P-09
0
2km
S
SHALLOW BAY
KUGMALLIT
RICHARDS
TAGLU
AKLAK
?FISH RIVER
①
②
③
④
⑤
TIME IN SECONDS
0
1
2
3
4
5
6
TIME IN SECONDS

Figure 9. Reflection seismic profile through the Adlartok P-09 well, west Beaufort. Location shown on Figure 1. 1: thrust-cored anticline with possible detachment in lower Tertiary strata; 2: angular unconformity betwen Aklak and Taglu strata; 3: truncation of Aklak-Taglu strata at sub-Richards unconformity; 4: low-angle truncation of Richards strata below sub-Kugmallit unconformity; 5: Shallow Bay Sequence. Seismic profile from COGLA report 025 09 08 021.





NORTH ISSUNGNAK
L-86
0
2km
N
0
1
2
3
4
5
TIME IN SECONDS
IPERK
AKPAK
MACKENZIE BAY
KUGMALLIT
KUGMALLIT SUBMARINE FAN
①
②
③
0
1
2
3
4
5
TIME IN SECONDS

Figure 10. Reflection seismic profile across the central Beaufort shelf. 1: northernmost major listric fault of the Tarsiut Fault Zone; 2: (?)submarine erosion of Kugmallit strata at sub-Mackenzie Bay unconformity; 3: truncation and basinward thinning of Mackenzie Bay deep water strata. Seismic profile from COGLA report 005 09 08 0110.

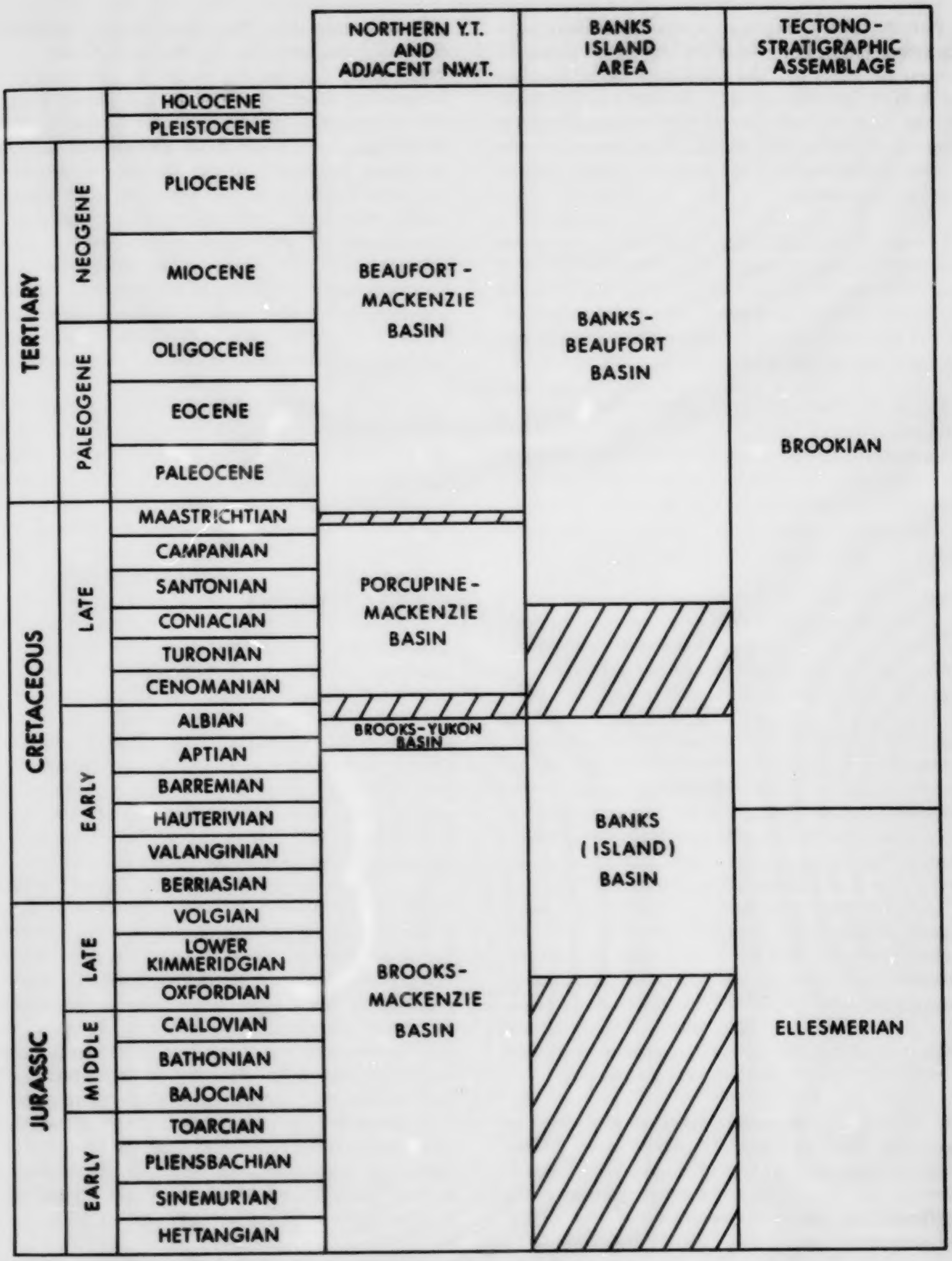

NORTHERN Y.T. AND ADJACENT N.W.T.
BANKS ISLAND AREA
TECTONO-STRATIGRAPHIC ASSEMBLAGE
HOLOCENE
PLEISTOCENE
TERTIARY
NEOGENE
PLIOCENE
MIOCENE
PALEOGENE
OLIGOCENE
EOCENE
PALEOCENE
CRETACEOUS
LATE
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
EARLY
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
JURASSIC
LATE
VOLGIAN
LOWER KIMMERIDGIAN
OXFORDIAN
MIDDLE
CALLOVIAN
BATHONIAN
BAJOCIAN
EARLY
TOARCIAN
PLIENSBACHIAN
SINEMURIAN
HETTANGIAN
BEAUFORT - MACKENZIE BASIN
PORCUPINE - MACKENZIE BASIN
BROOKS-YUKON BASIN
BROOKS - MACKENZIE BASIN
BANKS - BEAUFORT BASIN
BANKS (ISLAND) BASIN
BROOKIAN
ELLESMERIAN

Figure 11. Time-spatial relationships of the depositional basins identified in this report.

Yorath (1973) introduced the term Beaufort-Mackenzie Basin, but only in the title of his paper. In the text he refers to "the Mackenzie Delta-Beaufort Sea basin" (op. cit., p. 41). Nowhere is the basin defined. Yorath and Norris (1975) used the term "Beaufort-Mackenzie Basin" in a paper on the tectonic development of the area, but again without defining its meaning.

It was not until 1976 that the Beaufort-Mackenzie Basin was defined (Young et al., 1976). Young et al.'s usage was similar to that of Lerand (1973) for the Mackenzie Basin. However, the name Beaufort-Mackenzie Basin has been used more frequently and the name has gained acceptance.

Hea et al. (1980) defined the Mackenzie Basin as a pre-Tertiary feature, although in the bulk of their text it is apparent that they regard the Mackenzie Basin as containing only Paleozoic strata, a definition radically different from Lerand's (1973) original one. Hea et al. (op. cit.) defined the Beaufort-Mackenzie Basin as a Mesozoic-Tertiary depositional basin.

With the recognition of major interregional unconformities signifying tectono-stratigraphic boundaries, workers began to identify depositional basins based on stratigraphic limits and tectonic history (Figs. 12, 13). Balkwill et al. (1983) restricted strata above a major late Hauterivian unconformity (at the base of the Mount Goodenough Formation on the mainland) to the Beaufort-Mackenzie Basin, and the Carboniferous to middle Hauterivian strata to the Brooks-Mackenzie Basin. The latter was intended to imply a common stratigraphy and depositional history between the Yukon and northern Alaska. The late Hauterivian interregional unconformity has been used by several Canadian workers to separate two major tectono-stratigraphic assemblages (Fig. 11): the Carboniferous to middle Hauterivian Ellesmerian sequence and the younger late Hauterivian to Holocene Brookian sequence (Lerand, 1973; Norris and Yorath, 1981; Balkwill et al., 1983; Norris, 1985a). Lerand (1973) first defined the tectono-stratigraphic sequences of northwest Canada and adjacent Alaska.

In an earlier publication (Dixon et al., 1985) we suggested that the upper Hauterivian to Albian succession was part of a Yukon-Mackenzie Basin. However, we have revised our interpretation of the significance of various unconformities and of the paleogeographic setting and consider the name to be inappropriate. Therefore, we recommend abandoning the term.

In a recent U.S. Geological Survey publication discussing the geology of northwest Alaska (Gryc, 1988), many contributors revised the position of the Ellesmerian-Brookian boundary and placed it at the base of a thick succession of upper Aptian to Albian sediments. In the northern Yukon and adjacent Northwest Territories, Dixon (in press a) interpreted the same boundary as the beginning of a phase of mixed extensional and compressional tectonics. In Canada this late Aptian event also marks a change between pre-late Aptian epicratonic sedimentation with source terranes principally to the east and southeast, and late Aptian and younger sedimentation, during which the Cordillera was the principal source terrane and foreland basins formed (Dixon, 1986, in press a).

Within the Brookian sequence (sensu Lerand, 1973) of northern Yukon and the adjacent Northwest Territories, there are two, significant, tectono-stratigraphic unconformities that separate major depositional successions. The first, which also has been recognized as a major feature by others (Young, 1973; Yorath, 1973; Hawkings and Hatlelid, 1975), is between Albian and Upper Cretaceous strata. In the northern Cordillera the Upper Albian-lower Cenomanian unconformity separates indurated, fractured and highly faulted strata below from less well cemented, less dense and commonly more plastically deformed sediments above (Fig. 13). In parts of the Beaufort-Mackenzie Basin this unconformity acts as a structural décollement for the younger succession. Dixon (in press a) and Embry and Dixon (1990) interpreted this event as the breakup unconformity, subsequent to which Canada Basin opened and oceanic crust formed. Late Aptian and Albian sedimentation is characterized by Cordilleran source terranes and deep water troughs in the northern Yukon and adjacent Northwest Territories (Young et al., 1976; Dixon, 1986). Albian sedimentation appears to represent a transition between times of extension-dominant and compression-dominant tectonics (Dixon, in press a). Also during the Albian, older tectonic elements still influenced sedimentation patterns (e.g., the position of the deep-water troughs), whilst Cordilleran influences began to take over. Because of these transitional features and the common link with northern Alaska it is proposed that the broad-scale late Aptian and Albian depositional realm be referred to as the Brooks-Yukon Basin. By introducing this new basin term, Balkwill et al.'s (1983) Brooks-Mackenzie Basin is modified to include strata as young as early Aptian.

The second significant unconformity within the Brookian sequence formed during the Maastrichtian

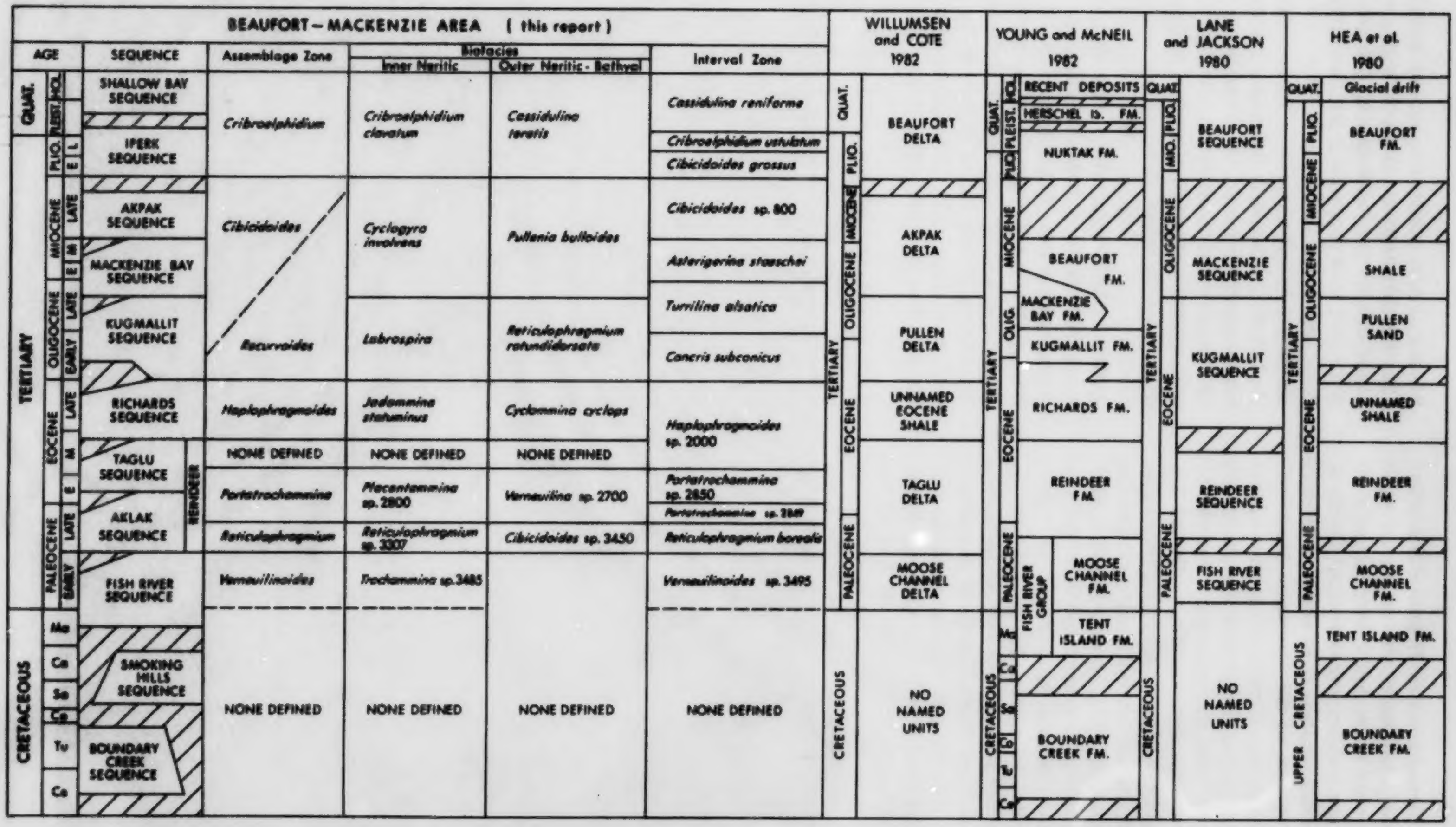

BEAUFORT – MACKENZIE AREA (this report)
AGE
SEQUENCE
Assemblage Zone
Biofacies
Inner Neritic
Outer Neritic - Bathyal
Interval Zone
WILLUMSEN and COTE 1982
YOUNG and McNEIL 1982
LANE and JACKSON 1980
HEA et al. 1980
QUAT.
TERTIARY
CRETACEOUS
UPPER CRETACEOUS
HOL.
PLEIST.
PLIO.
MIO.
MIOCENE
OLIGOCENE
OLIG.
EOCENE
PALEOCENE
E
L
M
LATE
EARLY
Ma
Ca
Sa
Co
Tu
Ce
SHALLOW BAY SEQUENCE
IPERK SEQUENCE
AKPAK SEQUENCE
MACKENZIE BAY SEQUENCE
KUGMALLIT SEQUENCE
RICHARDS SEQUENCE
TAGLU SEQUENCE
AKLAK SEQUENCE
REINDEER
FISH RIVER SEQUENCE
SMOKING HILLS SEQUENCE
BOUNDARY CREEK SEQUENCE
Cribroelphidium
Cibicidoides
Recurvoides
Haplophragmoides
NONE DEFINED
Portatrochammina
Reticulophragmium
Verneuilinoides
Cribroelphidium clavatum
Cyclogyra involvens
Labrospira
Jadammina statuminus
Placentammina sp. 2800
Reticulophragmium sp. 3307
Trochammina sp. 3485
Cassidulina teretis
Pullenia bulloides
Reticulophragmium rotundidorsata
Cyclammina cyclops
Verneuilina sp. 2700
Cibicidoides sp. 3450
Cassidulina reniforme
Cribroelphidium ustulatum
Cibicidoides grossus
Cibicidoides sp. 800
Asterigerina staeschei
Turrilina alsatica
Cancris subconicus
Haplophragmoides sp. 2000
Portatrochammina sp. 2850
Portatrochammina sp. 2849
Reticulophragmium borealis
Verneuilinoides sp. 3495
BEAUFORT DELTA
AKPAK DELTA
PULLEN DELTA
UNNAMED EOCENE SHALE
TAGLU DELTA
MOOSE CHANNEL DELTA
NO NAMED UNITS
RECENT DEPOSITS
HERSCHEL IS. FM.
NUKTAK FM.
BEAUFORT FM.
MACKENZIE BAY FM.
KUGMALLIT FM.
RICHARDS FM.
REINDEER FM.
FISH RIVER GROUP
MOOSE CHANNEL FM.
TENT ISLAND FM.
BOUNDARY CREEK FM.
BEAUFORT SEQUENCE
MACKENZIE SEQUENCE
KUGMALLIT SEQUENCE
REINDEER SEQUENCE
FISH RIVER SEQUENCE
Glacial drift
SHALE
PULLEN SAND
UNNAMED SHALE

Figure 12. Table of sequences, corresponding formational terminology, and biostratigraphic zonation (McNeil, 1989).

and divides the Cenomanian to Holocene succession into two distinct depositional phases. Cenomanian to Campanian sediments were deposited principally on the craton, in the northern Yukon and adjacent Northwest Territories, and the main depositional area will be referred to here as the Porcupine-Mackenzie Basin. Since Maastrichtian time, strata have been deposited mostly on the continental margin in the Beaufort Sea, and this depositional area will be referred to as the Beaufort-Mackenzie Basin. The Beaufort-Mackenzie Basin does contain Cenomanian to Campanian strata, but they do not represent the main period of deposition, rather they are the condensed and distal equivalents of the thicker deposits of the Porcupine-Mackenzie Basin.

The new, or modified, terms introduced are intended to cover large depositional areas and it is recognized that more local depositional subbasins may occur within them. For example the Bonnet Plume Basin, at the southern end of the Richardson Mountains, is a combined depositional, structural and preservational basin containing Upper Cretaceous strata that were deposited in the Porcupine-Mackenzie Basin, and lower Tertiary strata that were deposited in an interior basin, whereas the main deposition was in the Beaufort-Mackenzie Basin. For the most part, the basins identified herein are depositional basins, with stratigraphic and areal limits, although the latter are commonly ill-defined as a result of subsequent erosion of depositional edges.

Within the Beaufort-Mackenzie Basin a number of local features have been identified as basins. For example, Hea et al. (1980) introduced the terms "Jago Basin" (referred to more commonly as the Demarcation subbasin) and "Herschel Basin", the latter being a locally thick Tertiary succession between the Herschel and Blow River highs. We consider the Herschel feature principally a structural/preservational

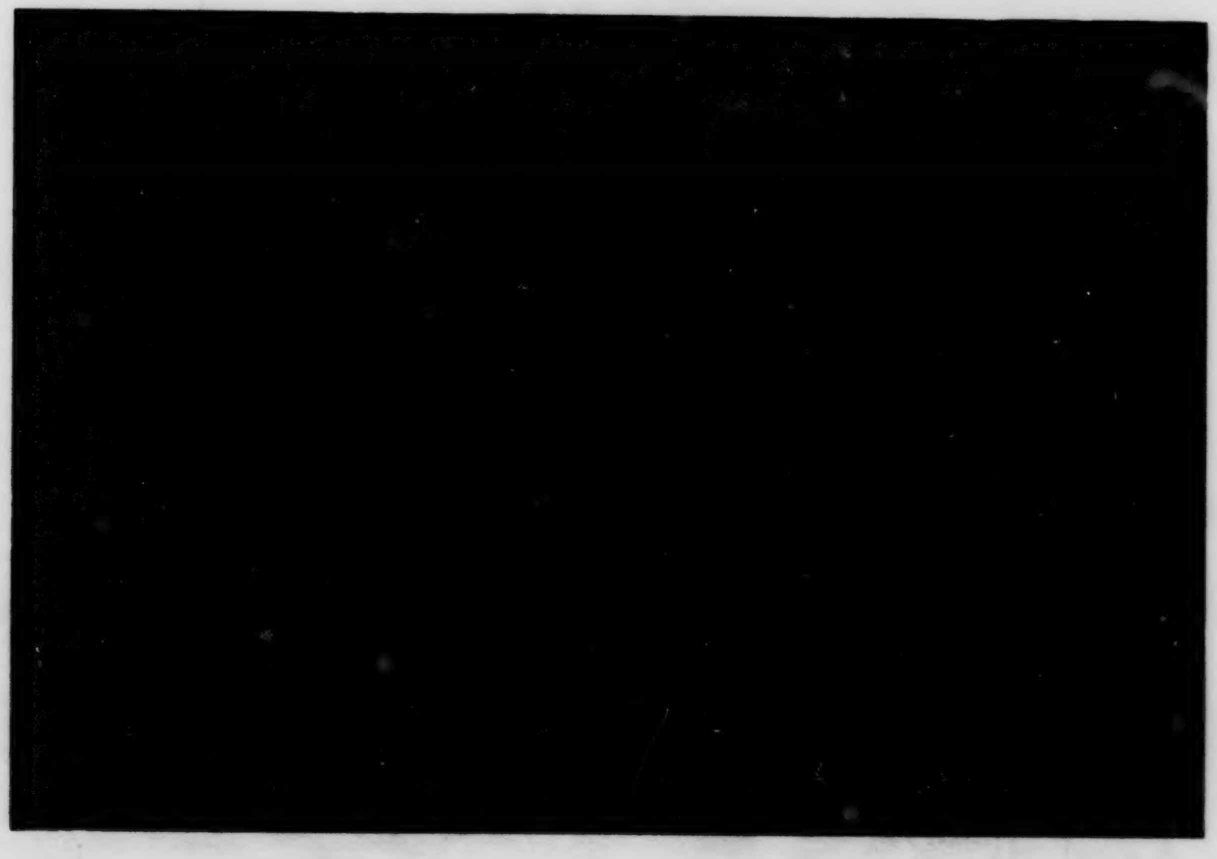


Figure 13. Contact between Albian shales and Boundary Creek Formation at Fish River. Note the detached fold in Boundary Creek shales (arrow). View to northeast. ISPG photo. 2236–7.

basin; it would be more appropriate to refer to it as the Herschel Depression. The Demarcation subbasin was a local Late Eocene to Miocene depocentre, modified by Late Miocene tectonics and erosion.

Young and McNeil (1984, p. 4) identified the Richards Island Basin as a depression that " . . . developed as a consequence of Laramide tectonism in the landward margins of the **earlier Beaufort-Mackenzie Basin**" [emphasis added]. Implicit in this statement is that the Richards Island Basin contains principally Cenozoic sediment. On a regional scale there is little evidence to indicate that a separate Cenozoic depositional basin existed under Richards Island; in fact, the Cenozoic sediments are part of the Beaufort-Mackenzie Basin (sensu this report). As will become apparent in a later part of this report, the Richards Island area was a local depocentre within the Beaufort-Mackenzie Basin during part of the early Tertiary.

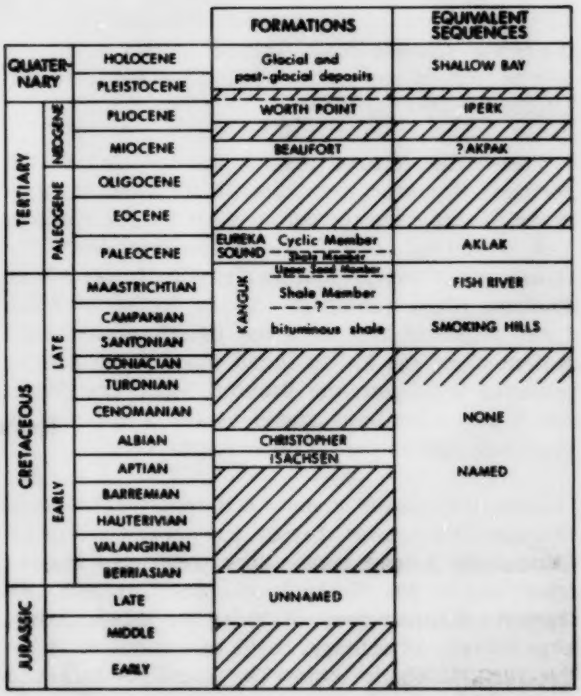
The sediment fill of the Beaufort-Mackenzie Basin is contiguous with sediments of the Kaktovik Basin (Grantz et al., 1979), offshore eastern Alaska. There is little structural differentiation between the two basins and they may have been contiguous depositional basins.

Banks Island and offshore

Cenozoic strata of the northeastern Beaufort-Mackenzie Basin are contiguous with those in the far offshore of Banks Island. However, the limited seismic data across and seaward of Amundsen Gulf provide only direct correlation of Plio-Pleistocene strata and very tentative correlations of thin sections of older Tertiary strata from the Beaufort-Mackenzie Basin into the nearshore Banks Island area. Furthermore, as will be demonstrated below, facies trends indicate that the Banks Island area received its sediment from a different source direction, at least prior to the Pliocene. Consequently, we propose a separate basin designation for the latest Cretaceous-Cenozoic fill (Figs. 11, 14). The boundary between the two depositional basins is diffuse, extending through Amundsen Gulf across the Beaufort shelf.

Thorsteinsson and Tozer (1960, Fig. 2) first used the term "Banks Island Basin" on a tectonic map of the Arctic Islands. From their map it is apparent that the basin was intended to include strata between the Isachsen Formation (Lower Cretaceous) and Tertiary strata (Fig. 14). Lerand (1973) followed their usage but shortened the term to "Banks Basin". Miall (1974, 1975, 1979) recognized a number of local uplifts and depressions that subdivided the basin into subbasins, of which he named five. Also, with the availability of results from exploration drilling, Jurassic strata were recognized in the central part of Banks Island.

The tectono-stratigraphic boundaries recognized in the mainland stratigraphic succession can be identified in the Banks Island strata. Ellesmerian strata include the Jurassic to Aptian, pre-Christopher Formation strata preserved only in the central part of Banks Island. The Christopher, Hassel, Kanguk, Eureka Sound, Beaufort, and Worth Point formations are part of the Brookian sequence. At least one of the two major Brookian unconformities identified in the Albian to Holocene strata of mainland Canada is present on Banks Island, at the base of the Upper Cretaceous Kanguk Formation. The younger unconformity is not identified, but there is a significant downlap surface at the top of the bituminous shale of the Kanguk Formation that is approximately the same age. It is our intent to use the term "Banks-Beaufort Basin" for the offshore and onshore depositional basin



FORMATIONS
EQUIVALENT SEQUENCES
QUATERNARY
HOLOCENE
PLEISTOCENE
Glacial and post-glacial deposits
SHALLOW BAY
TERTIARY
NEOGENE
PLIOCENE
WORTH POINT
IPERK
MIOCENE
BEAUFORT
? AKPAK
PALEOGENE
OLIGOCENE
EOCENE
PALEOCENE
EUREKA SOUND
Cyclic Member
Shale Member
AKLAK
Upper Sand Member
KANGUK
Shale Member
?
bituminous shale
FISH RIVER
SMOKING HILLS
CRETACEOUS
LATE
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
NONE
NAMED
EARLY
ALBIAN
CHRISTOPHER
ISACHSEN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
JURASSIC
LATE
UNNAMED
MIDDLE
EARLY

Figure 14. Lithostratigraphic and sequence nomenclature of Mesozoic and Tertiary strata on Banks Island. (Lithostratigraphy modified from Miall, 1979.)

that includes only latest Cretaceous to Cenozoic strata of the Kanguk to Worth Point formations, and geographically includes Banks Island and the adjacent offshore part of the Beaufort Sea. The subbasin terms defined by Miall are more appropriately limited to pre-Kanguk strata.

PLATE TECTONIC SETTING

The origins of the Porcupine–Mackenzie and Beaufort–Mackenzie basins are intimately related to the origin of Canada Basin in the Arctic Ocean and the evolution of the Cordilleran orogen (Dixon, in press a; Embry and Dixon, 1990). Of the numerous dynamic models proposed for the opening of Canada Basin (see Lawver et al., 1984, for a review) the most commonly accepted model, and the one that appears to best fit the known geology of the circum-Canada Basin areas, is the rotation model of Carey (1958), Tailleur and Brosge (1970), and Tailleur (1973), and expanded upon by Grantz et al. (1979). This model assumes that prior to about mid-Cretaceous time, northern Alaska was juxtaposed against the Arctic Islands. Beginning in either Hauterivian (Grantz et al., 1979) or Late Albian/early Cenomanian time (Embry and Dixon, 1990), counterclockwise rotation separated the two plates and Canada Basin formed. In this model the pole of rotation was probably located within the Rapid Depression (Norris, 1983).

Post-Albian regional tectonic activity has involved northerly to northeasterly directed thrusting of strata in the Brooks Range of northern Alaska, the northern Yukon and adjacent offshore Beaufort Sea. The thrusting has overprinted and modified part of the southern rifted margin of Canada Basin. McWhae (1986) suggested that there was significant strike-slip motion along the Kaltag–Rapid Fault Array and its projected trend into the Beaufort–Mackenzie Basin, which may have been caused by the Siberian plate impinging against the northern Alaska plate.

Using the rotation scenario it is apparent that rapid thermal subsidence during the Cenomanian to Campanian helped create deep, restricted marine conditions in the Banks Island–Beaufort area. As thermal subsidence declined during the Maastrichtian, large volumes of sediment began to accumulate in the Beaufort–Mackenzie Basin. The Beaufort–Mackenzie Basin formed near the apex of rotation and, subsequent to rifting, thermal subsidence of the drifting continental margin would have enhanced its attributes as a locus for sediment accumulation. Furthermore, vast amounts of sediment were being shed onto the Yukon–Alaska continental margin from the rising Cordillera to the south and southwest, adding an extra loading factor to the thermal subsidence. Banks–Beaufort Basin is essentially part of the rifted continental margin of the Arctic Islands with a sediment source from the east and southeast. It appears not to have been subjected to much Late Cretaceous–Tertiary tectonic activity, nor was the sediment provenance an orogenic belt. Post-Albian sedimentation has resulted in the accumulation of 12 to 16 km of strata in the Beaufort–Mackenzie Basin (Fig. 15), with the thickest accumulation centred under the outer shelf north of Mackenzie Delta.

PRE-UPPER CRETACEOUS STRATIGRAPHY

Albian and older strata form the structural-stratigraphic basement on which sediments of the Porcupine–Mackenzie, Beaufort–Mackenzie and Banks–Beaufort basins were deposited. Their known and conjectured distribution below the basin-fill sediments is shown in Figure 16. The map is based on outcrop, exploration borehole and reflection seismic data. Under much of the basins, Albian strata subcrop below Upper Cretaceous rocks: Christopher Formation on Banks Island and the nearshore areas, Horton River Formation in the Anderson Plains, Arctic Red Formation under Tuktoyaktuk Peninsula and adjacent nearshore areas, and the informally named Albian flysch west of the Mackenzie Delta.

Proterozoic strata are present at the south end of Banks Island, in the Cape Lambton Uplift (Figs. 1, 3; Miall, 1976). On the mainland, Proterozoic strata outcrop in the Campbell Lake Uplift and are interpreted as being present under Tuktoyaktuk Peninsula (Dixon, 1979; Wielans, 1987, 1988a, b). Lane and Cecile (1989) reported the presence of lower Paleozoic strata on the northeast flank of the Romanzof Uplift; consequently, Proterozoic strata reported in the Romanzof Uplift (Norris, 1985b) may not be as extensive as previously thought. Cambrian to Middle Devonian sediments under Banks Island and east and southeast of Mackenzie Delta consist of basal clastic sediments (Cambrian) overlain by a thick accumulation of platform carbonates (Upper Cambrian to Middle Devonian; Thorsteinsson and Tozer, 1962; Miall 1976; Pugh, 1983). In the Richardson and British mountains, age-equivalent strata consist of basinal deposits such as shale, phyllite, argillite, and chert. Under the Beaufort Sea shelf off western Banks Island, reflection seismic data indicate the presence of a thick succession of presumed Paleozoic and Proterozoic strata subcropping under Upper Cretaceous–Tertiary beds (Figs. 8, 16). Upper Devonian strata on Banks Island and the mainland consist of a thick clastic wedge (Melville Island Group on Banks Island, Canol and Imperial formations on the mainland).

Carboniferous and Permian strata outcrop only in the Richardson and British mountains, west of the Mackenzie Delta (Fig. 1; Bamber and Waterhouse, 1971; Bamber, 1973) and consist of clastic rocks (Kayak and Kekiktuk formations) overlain by carbonates (Lisburne Group). Their known subsurface occurrence is limited to the southwestern edge of Mackenzie Delta. They appear to be absent east of Mackenzie Delta and in the Banks Island area.

Triassic sandstone, shale and carbonates are present in only a few areas adjacent to the British Mountains, such as the Loney Syncline (Norris, 1981a). They appear to be absent in the subsurface of the Mackenzie Delta area.

Jurassic to Albian clastic sediments are extensively exposed on the mainland and are known in the subsurface of southern Mackenzie Delta and Tuktoyaktuk Peninsula. They are thickest in the Rapid Depression and Kugmallit Trough. Jurassic and Lower Cretaceous strata consist of alternating shale- and sandstone-dominant units south and southeast of Rapid Depresssion, grading laterally to the west and northwest into a shale-dominant succession (Young, 1973; Miall, 1979; Poulton, 1982; Poulton et al., 1982; Dixon, 1982, 1986).

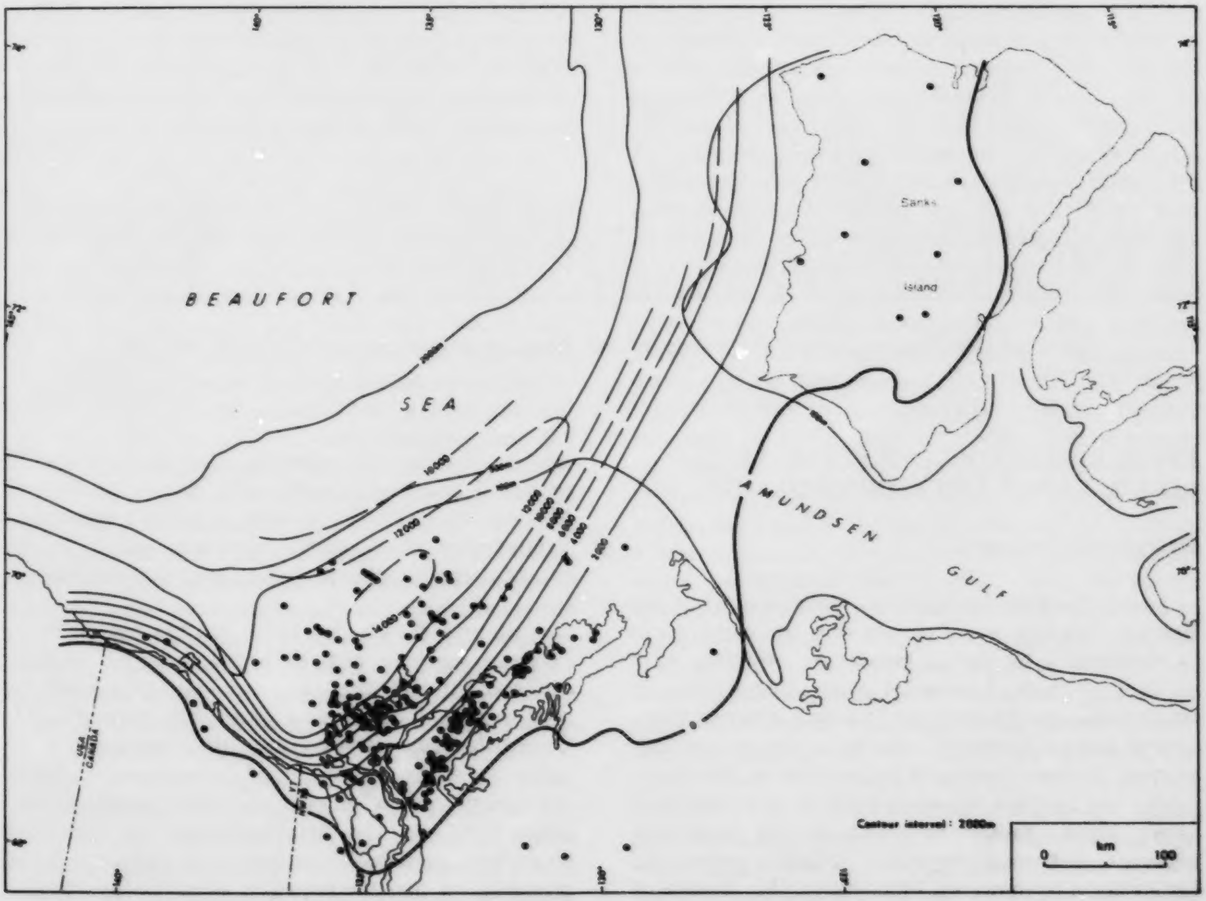


Figure 15. Isopach of Upper Cretaceous to Quaternary strata. Values derived principally from reflection seismic.

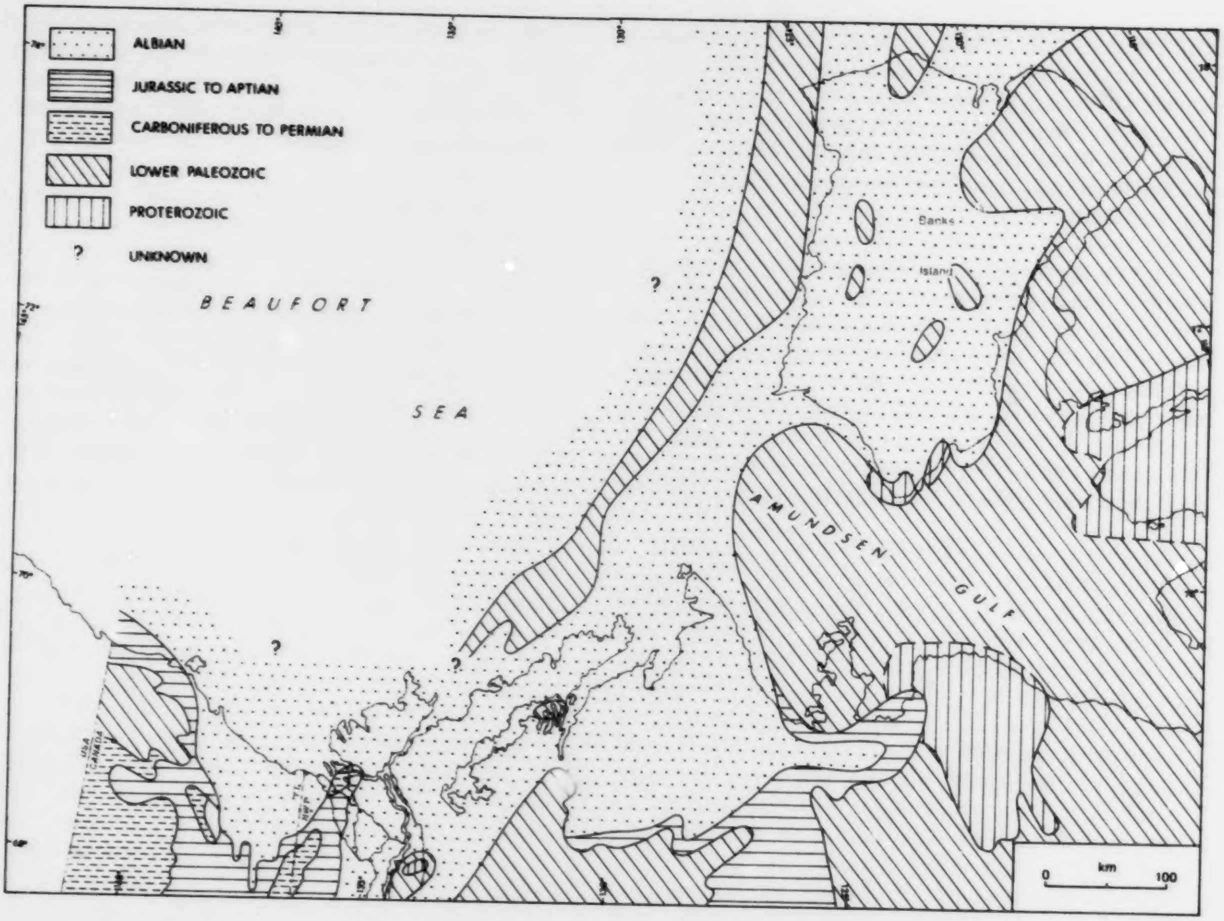


Figure 16. Pre-Upper Cretaceous geology of the Beaufort–Mackenzie and Banks Island areas.

UPPER CRETACEOUS–HOLOCENE STRATIGRAPHY AND SEDIMENTOLOGY

Stratigraphic concepts

Late Cretaceous to Holocene sedimentation on the Beaufort Sea continental margin was, and continues to be dominated by deltaic processes, resulting in a number of thick, basinward prograding wedges of clastic sediment. At the locus of deltaic sedimentation, coarse clastic sediment dominates the succession, whereas in more basinward locales shale is dominant. Under the modern Mackenzie Delta and nearshore areas, thick, sandstone-prone deltaic sediments alternate with mudstone-rich prodeltaic sediments, facilitating a conventional lithostratigraphic division of the succession (Young and McNeil, 1984). However, in much of the offshore the succession is mostly shale and siltstone, and conventional lithostratigraphic divisions are less obvious. Consequently, Dietrich et al. (1985) proposed that the depositional sequence concept of Mitchum et al. (1977) be used to identify basin-wide stratigraphic units, using reflection seismic as the principal stratigraphic tool (i.e., seismic stratigraphy).

Vail and Mitchum (1977, p. 51) stated that, "Seismic sequence analysis is based on the identification of stratigraphic units composed of a relatively conformable succession of genetically related strata termed **depositional sequences** [their emphasis]. The upper and lower boundaries of depositional sequences are unconformities or their correlative conformities" (Fig. 17A). In the original work by Vail and co-workers the depositional sequence model was based primarily on the interpretation of reflection seismic, although they did state that seismic and depositional sequences were equivalent, insofar as the limits of conversion from seismic to rock units would allow.

In subsequent years the Exxon team of Vail and co-workers began to refine and add to their depositional sequence model. One of the more significant changes was in the refinement of what constitutes the conformable equivalent of the basin margin unconformity. Also, the depositional sequence model became less reliant on the interpretation of reflection seismic and more a theoretical depositional model based on a sinusoidal sea-level curve and the resulting stratal patterns. Vail et al. (1984) and Haq et al. (1987) added to the sequence concept by identifying condensed sections and subdividing sequences into depositional systems tracts (Fig. 17A). Posamentier et al. (1988) and Posamentier and Vail (1988) enlarged upon the definition and characteristics of the depositional system tracts of depositional sequences and their relationships to eustasy. Much of the Exxon work relating the depositional sequence model to the rock record has concentrated on basin margin successions where unconformity, ravinement and flooding surfaces are commonly readily recognized. At present, few studies have applied the model to conformable marine succcessions. Consequently, criteria for identifying the conformable equivalent of the basin margin unconformity are lacking.

Seismic and depositional sequences are considered to be physically equivalent and the reflection of the basin margin unconformity should be traceable into an equivalent conformable surface within the basin. However, Embry (1983, 1989) and Embry and Podruski (1988) questioned whether the equivalent conformable surface of the basin margin unconformity can be objectively identified. They pointed out that basinward of the marginal unconformity there are several, commonly closely spaced, and even locally merged, erosional and depositional surfaces within strata near or at a sequence boundary. In such a setting these surfaces could be encompassed within a single reflection on a seismic profile. They pointed out that in marine basins, an unconformity is commonly capped by sandy transgressive beds, in turn abruptly overlain by shales/mudstones. They identified the abrupt upper lithological contact as a submarine unconformity (hiatal surface, sensu Frazier, 1974; a downlap surface of Vail and co-workers, 1977). This unconformity is likely to be a reflecting surface within a marine basin, especially if the transgressive beds are thin and overlie a similar rock type (Fig. 17A, B). Vail et al. (1984) began to recognize this problem and identified it as a flooding surface at the base of a condensed section, in turn overlain by downlapping beds.

Some of these problems had been foreseen by Frazier (1974) who proposed a depositional model based on the Mississippi Delta sediments. Frazier called each regressive-transgressive sediment package a depositional-complex (Fig. 17B), formed during a depositional episode. He noted that sandy transgressive beds could overlie sandy progradational strata and that the plane of unconformity would be difficult to identify in such a situation, but that hiatal surfaces (submarine unconformities, flooding surfaces) are more readily identified; hence, he used them as the bounding surfaces of the depositional-complexes. Galloway (1989) resurrected Frazier's model, made further refinements, and renamed the depositional-complexes genetic stratigraphic sequences.

The main difference between the two sequence models is the choice of bounding surfaces: unconformities as opposed to hiatal (flooding) surfaces. For practical purposes, the bounding surface of a seismic sequence is a single reflection, but when attempting to identify the corresponding boundaries in a rock succession, whether using the lithological succession or geophysical logs, it is important to correctly identify the boundary types: an unconformity, transgressive surface, or a hiatal surface/flooding surface. Some of these problems have been discussed by Dixon and Dietrich (1988) with respect to the Beaufort-Mackenzie area. The difficulty in recognizing the conformable equivalent of the basin margin unconformity and in identifying the shelf margin wedge depositional systems tract from well data made it necesssary to use either the transgressive surface or the flooding/hiatal surface as the closest approximation to a seismically defined sequence boundary in conformable successions. The sequences we identify are essentially transgressive-regressive cycles and are different from the depositional sequences presently defined by Vail and co-workers, although there are similarities to the originally defined seismic sequences of Mitchum et al. (1977). We use the unconformity as the bounding surface where it can be recognized, usually at the basin margin, and the transgressive or flooding surface within the conformable succession of the basinward part of the sequence. Although we recognize that the transgressive and flooding surfaces commonly are separate, our experience in the Beaufort area has shown that the surfaces are difficult to separate in marine and deltaic successions on reflection seismic profiles and well logs. Also, there appear to be areas where the two surfaces merge, or are separated by such a thin interval that for practical purposes they are one surface.

The methodology we have applied to the Beaufort-Mackenzie and Banks-Beaufort successions is practical and objective. One possible area of contention in applying the transgressive-regressive depositional model is the placing of thick submarine fan successions — do they belong to separate T-R cycles or are they the lower or upper parts of T-R cycles? We can identify three major submarine fan wedges: the Maastrichtian Cuesta Creek strata, early Oligocene beds (which Dietrich et al., 1985, originally identified as the Kopanaor Sequence), and basal beds of the Iperk Sequence in parts of the offshore areas. Until the T-R model is further refined and this issue is resolved, we have placed the three major submarine fan deposits at the base of sequences, which is similar to the Vail/Exxon approach.

The sequences in the Upper Cretaceous to Holocene succession of the Beaufort-Mackenzie and Banks Island areas have been identified from a combination of seismic data, well data and, to a lesser extent, outcrop information. Outcrops of Upper Cretaceous and Tertiary strata are not very extensive but are sufficient to allow for the identification of some primary boundaries, principally in Upper Cretaceous to Oligocene strata. Younger strata are poorly represented to nonexistent in outcrop; consequently, boreholes are the source of lithological and biostratigraphic information. The principal areas of outcrop are the northern Richardson Mountains and the Yukon coastal plain (Young, 1975), Caribou Hills (Price et al., 1980), Anderson Plain (Yorath et al. 1975; Yorath and Cook, 1981), and Banks Island (Plauchut and Jutard, 1976; Miall, 1979). While the cited authors have produced the most extensive descriptions and interpretations of the geology, J. Dixon (one of the present authors) has visited most of the mainland outcrop areas.

Sequence boundaries on seismic data are most clear in areas where discordant reflection patterns occur as a result of subaerial or submarine truncation of strata below the sequence boundary (e.g., Figs. 4, 6, 9). The seismically visible angular unconformities occur in geographically restricted portions of the basin, along paleobasin margins, shelf edges, and locally on

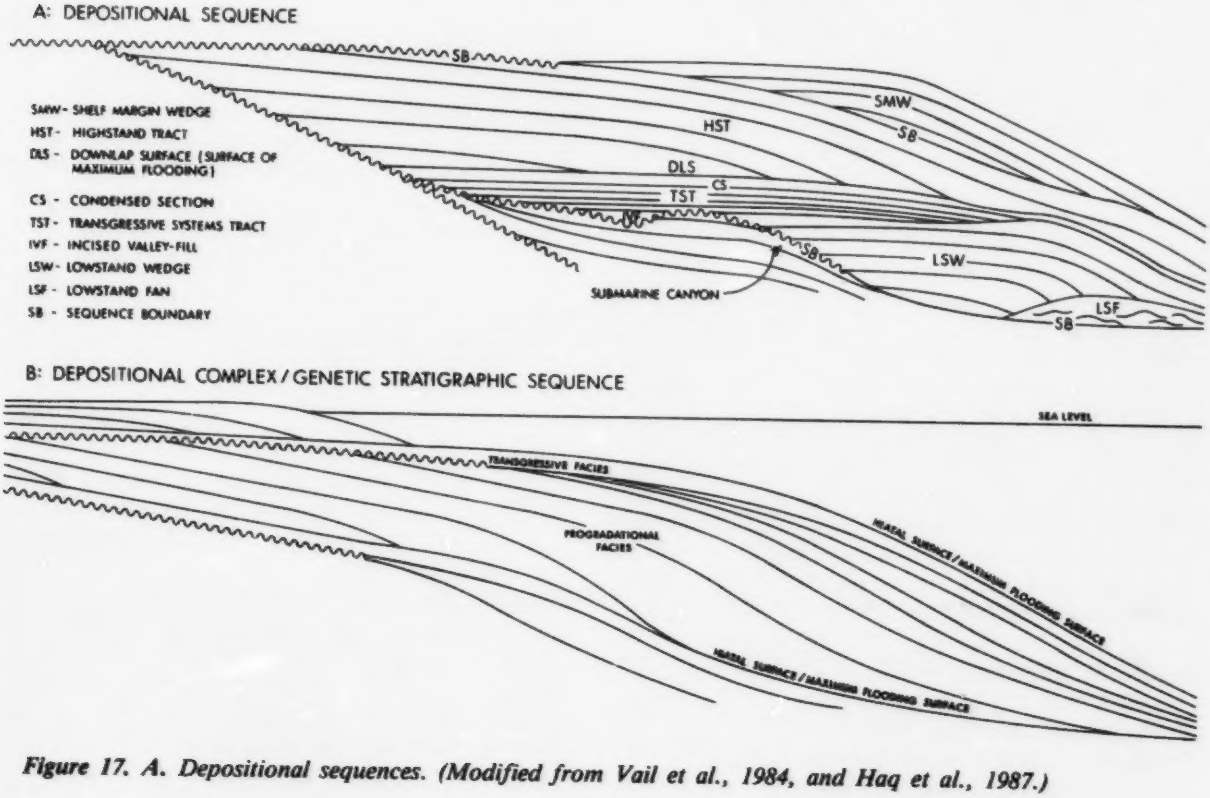

A: DEPOSITIONAL SEQUENCE
SB
SMW
HST
SB
DLS
CS
TST
IVF
SB
LSW
SUBMARINE CANYON
LSF
SB
SMW - SHELF MARGIN WEDGE
HST - HIGHSTAND TRACT
DLS - DOWNLAP SURFACE (SURFACE OF MAXIMUM FLOODING)
CS - CONDENSED SECTION
TST - TRANSGRESSIVE SYSTEMS TRACT
IVF - INCISED VALLEY-FILL
LSW - LOWSTAND WEDGE
LSF - LOWSTAND FAN
SB - SEQUENCE BOUNDARY
B: DEPOSITIONAL COMPLEX / GENETIC STRATIGRAPHIC SEQUENCE
SEA LEVEL
TRANSGRESSIVE FACIES
PROGRADATIONAL FACIES
HIATAL SURFACE / MAXIMUM FLOODING SURFACE
HIATAL SURFACE / MAXIMUM FLOODING SURFACE

Figure 17. A. Depositional sequences. (Modified from Vail et al., 1984, and Haq et al., 1987.)

B. Depositional-complexes/genetic depositional sequences. (Modified from Frazier, 1974 and Galloway, 1988.)

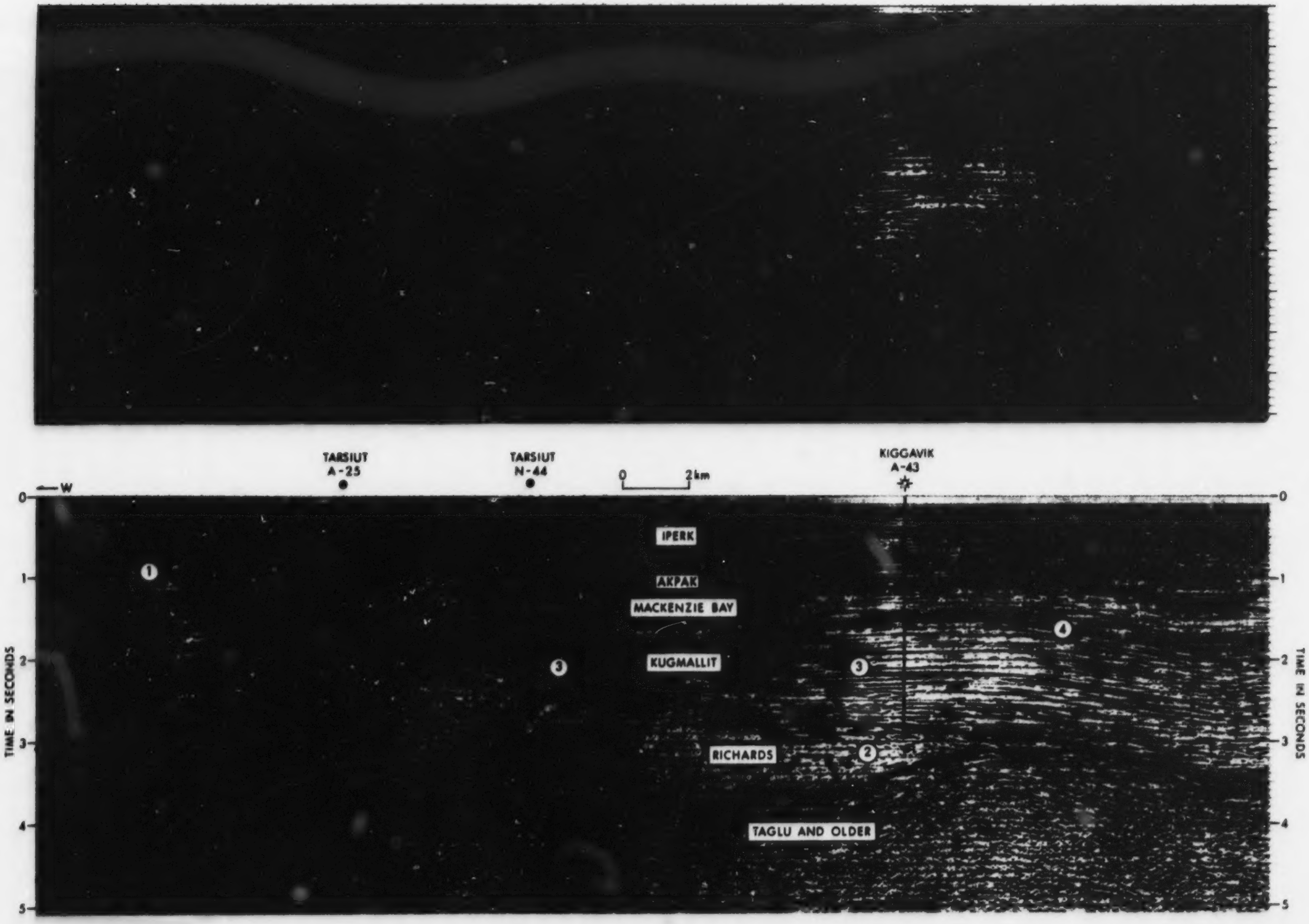


Figure 18. *Reflection seismic profile across the central Beaufort shelf. Location shown on Figure 1. 1: high-amplitude, continuous reflections at the base of the Iperk Sequence; 2: truncation of Richards strata below sub-Kugmallit unconformity; 3: divergent, shingle reflections within distal delta front deposits of the Kugmallit Sequence; 4: baselap of reflections at base of Mackenzie Bay Sequence. Seismic profile from COGLA report 005 09 08 0110.*

syndepositional growth structures. Discordant reflection patterns above sequence boundaries include downlap and onlap of strata onto an unconformity or flooding surface (e.g., Figs. 6, 10). Downlapping reflections also occur locally in intra-sequence positions (e.g., prograding continental slope beds) and as such are less reliable than other reflection patterns in identifying sequence boundaries. The most areally extensive sequence boundaries in the basin occur within seismically conformable or near-conformable successions. Some of the conformable seismic sequence boundaries can be identified from the abrupt vertical changes in seismic facies (e.g., Figs. 5, 10), or a high amplitude, continuous reflection at the boundary itself (e.g., Fig. 18). The seismic facies variations result from differences in lithology and/or bed thickness between sequences. High-amplitude sequence boundary reflections occur locally as a result of acoustically distinct units such as coarse grained transgressive deposits or, more rarely, diagenetic carbonate beds. In some parts of the basin there are no obvious seismic expressions of some of the conformable sequence boundaries and the sequence identifications rely more on available well data (wireline logs and/or biostratigraphic data). Well log correlations of the sequences in the Beaufort and Banks Island areas are illustrated in Figures 19 to 23 (in pocket). On well logs, sequence boundaries can be readily recognized where lithological contrasts occur across the boundary. In lithologically similar successions (e.g., marine shales) the sequence boundaries commonly can be identified on sonic logs. Abrupt shifts in the gradient of sonic transit time can occur across sequence boundaries as a result of differences in compaction, porosity or silt content (Fig. 24).

Sequences result from the **relative** rise and fall of sea level [authors' emphasis] and can be local, regional or interregional in extent. In the Beaufort-Mackenzie and Banks Island areas we have attempted to identifiy regionally extensive sequences. The sequences we have identified would rank as second and third order sequences. Higher rank sequences can be recognized on a local scale (e.g., Morrell and Schmidt, 1988) but, to date, we have not been able to correlate these sequences throughout the Beaufort-Mackenzie and Banks-Beaufort basins.

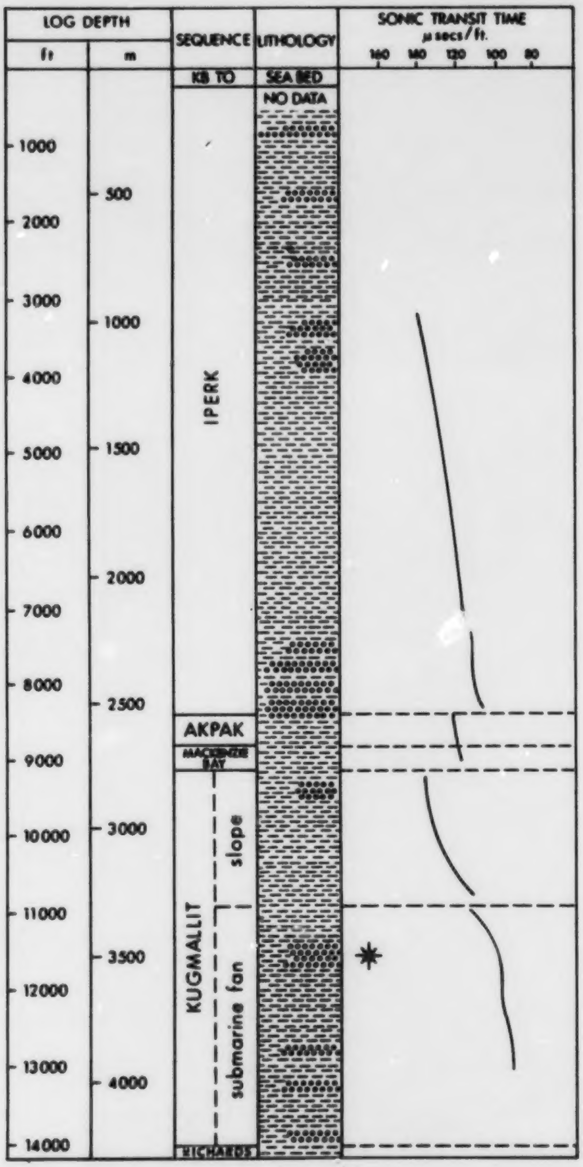


Figure 24. Plot of shale sonic transit time against depth. Note that many of the sequence boundaries correspond approximately to changes in the slope gradient (Kopanoar M-13).

Sequences may be classified as operational or parastratigraphic units (Bates and Jackson, 1980, p. 437), although under the revised North American Stratigraphic Code (The North American Commission on Stratigraphic Nomenclature, 1983) the unconformity-bounded parts of the identified sequences could be classified as allostratigraphic units. Other than allostratigraphic nomenclature, which has guidelines similar to lithostratigraphic nomenclature, there are no rules or guidelines for naming depositional, genetic stratigraphic, or transgressive-regressive sequences. At the time Dietrich et al. (1985) began to name the sequences in the Beaufort-Mackenzie Basin, no rules or guidelines had been adopted for the identification and naming of sequences. Consequently Dietrich et al. (1985) proposed that in the Beaufort-Mackenzie area the conventional lithostratigraphic unit most closely corresponding to the depositional sequence should be used to name the sequence (Fig. 12). It was noted early in our investigations that many of the formational boundaries corresponded to the sequence boundaries, or were in very close stratigraphic proximity. However, it should be pointed out that the name has no lithological connotations when used as the sequence designator. For example, the Kugmallit Formation is a sandstone-dominant unit that closely corresponds to the basin margin part of a sequence, hence the same name has been applied to the sequence. Basinward, the same sequence becomes mudstone-dominant. In lithostratigraphic practices a new name would have to be used, but in sequence identification it is the same unit and therefore should be identified as the same, regardless of facies. Although we recognize the potential for confusion by using formational names as part of the sequence terminology, the precedent was set (Dietrich et al., 1985) on what we still believe to be a useful and practical adaptation of the pre-existing nomenclature.

Eleven regionally extensive sequences have been identified in Upper Cretaceous to Holocene strata of the Beaufort-Mackenzie Basin (Fig. 12), a few of which can be recognized in the Banks-Beaufort Basin on the basis of seismic or biostratigraphic correlations (Fig. 14). In ascending order these have been named: Boundary Creek, Smoking Hills, Fish River, Aklak, Taglu, Richards, Kugmallit, Mackenzie Bay, Akpak, Iperk, and Shallow Bay. It could be argued that the two basins should have separate sequence names, but the present study is a preliminary evaluation of the sequence stratigraphy of the Banks Island area, and we do not wish to introduce new sequence terminology until more detailed studies and integration of onshore seismic and well data are undertaken.

Depositional facies assemblages

Five of the eleven depositional sequences identified in the study area contain large delta complexes. Consequently, a common set of depositional facies assemblages can be identified: 1) fluviodeltaic, 2) prodelta/shelf, and 3) deep water. Each of the depositional facies assemblages has been identified from lithological associations, log shapes and from sedimentological interpretations of available cores and outcrops. This type of approach to facies identification in the Beaufort-Mackenzie area has been used previously by Young et al. (1976). The seismic expression of the general depositional facies assemblages can be described in terms of reflection geometry, continuity and amplitude, some aspects of which have been described previously (Dixon et al., 1984, 1985; Dietrich et al., 1985, 1989). However, some of the depositional facies assemblages have a number of seismic characteristics in common and regional facies mapping requires the integration of seismic and well data.

Fluviodeltaic facies assemblage

Within the fluviodeltaic realm a number of depositional subenvironments are recognized, each with a distinct lithological succession: 1) alluvial/upper delta plain, 2) lower delta plain and delta front, and 3) distal delta front.

Alluvial/upper delta plain

Deposits of the alluvial/upper delta plain environments are dominated by fluvial channel and floodplain sediments. Channel deposits commonly consist of fining-upward conglomerate and sandstone successions capped by floodplain deposits consisting of thinly interbedded shale, siltstone and sandstone, and in some sequences, coal beds. Channel deposits may contain fine sand to cobbles; they invariably rest on an erosion surface and in many cases contain internal scour surfaces. Coarse clasts are commonly restricted to the basal parts of channel deposits and may be extrabasinal (mostly chert and sandstone, with some volcanic clasts) or intrabasinal (shale and coal are the most common) in origin. Where coarse clastic sediment is dominant in a channel deposit, sedimentary structures are commonly difficult to detect, although crude alignment of clasts or alternations of differing clast sizes may be present, indicating the presence of crossbeds. As the clast size decreases, sedimentary structures tend to be more conspicuous and planar and trough crossbeds are the principal structures, although structureless sand probably is the most common feature of channel deposits. As the grain size further decreases upsection and more clay-sized particles become common, sedimentary structures are more readily seen, and fine, subparallel laminae and current-ripple laminae are the most common features. Individual channel deposits range in thickness from several metres to a few tens of metres. However, where multistorey channel deposits are present and intervening floodplain deposits have been eroded, thick vertical successions of sandstone and conglomerate, up to hundreds of metres thick, may occur at the basin margins of some sequences.

Floodplain deposits consist of thin beds of shale, siltstone and sandstone. Individual beds are generally a few centimetres to a few metres thick, and floodplain intervals a few metres to several tens of metres thick. Subhorizontal and current-ripple laminae are the most common structures in the siltstones and sandstones, with low-angle, planar crossbedding and small-scale trough crossbeds also present. Structureless sandstone beds also are common. Root zones in siltstones and sandstones are locally present, especially if coal beds occur in the succession. Floodplain deposits can be attributed to a variety of subenvironments, such as ponded areas, freshwater lakes, marshes, swamps, levees, crevasse channels, and crevasse splays.

Successions dominated by alluvial/upper delta plain deposits typically contain greater than 60 per cent sandstone/conglomerate; resistivity/SP/gamma-ray log traces tend to have a blocky, indented shape, and commonly reflect the fining-upward aspect of the channel-to-floodplain deposits (Fig. 25). Examples of alluvial/upper delta plain deposits are present in the coal-bearing Aklak and Fish River sequences of Natsek E-56, in parts of the Aklak and Taglu sequences of Ellice O-14 and Fish River B-60, and in the uppermost beds of the Kugmallit Sequence in the Ivik wells on the Mackenzie Delta. Outcrops of alluvial/upper delta plain deposits are not common; examples are in the Aklak Sequence at Aklak Creek (the Aklak Member of the Reindeer Formation of Young, 1975) and Caribou Hills (Price et al., 1980).

Lower delta plain and delta front

Lower delta plain and delta front deposits consist of large-scale coarsening-upward cycles several tens to 300 m thick, which contain prodelta muds at the base that grade up into delta front sand and mud, succeeded in turn by nonmarine and marginal marine deposits of the lower delta plain (Fig. 26). The nonmarine beds are very similar to those of the alluvial/upper delta plain, in that channel and floodplain deposits are dominant (seen as fining-upward units in core and log shapes). However, thick, uninterrupted sandstone successions are less common; there tends to be more interbedded shale, and marine influences, such as the occurrence of interdistributary bay and strandplain deposits are more apparent. Also, coal deposits are absent or extremely thin and argillaceous. Details of the lower delta plain and delta front facies can be found in Dixon's (1981) description of the Taglu Delta deposits.

Each of the coarsening-upward units in the lower delta plain and delta front subfacies represents the progradation of a single, major, delta lobe. The stacking of such deposits results from delta switching, a consequence of subsidence and transgression, resulting in vertical and lateral repetition of similar facies.

Lower delta plain and delta front depositional facies are common in the fluviodeltaic deposits of the Aklak, Taglu and Kugmallit sequences. Wells that penetrate the outer fringes of the subaerial parts of delta complexes can contain many hundreds of metres of such deposits. Examples in the Taglu Sequence include the Taglu, Kumak and Niglintgak wells; in the Richards Sequence the Ivik wells; and in the Kugmallit Sequence, the Pullen E-17 well. Some of the Fish River Sequence on Fish River, northern Richardson Mountains (Moose Channel Formation), contains strata of this facies.

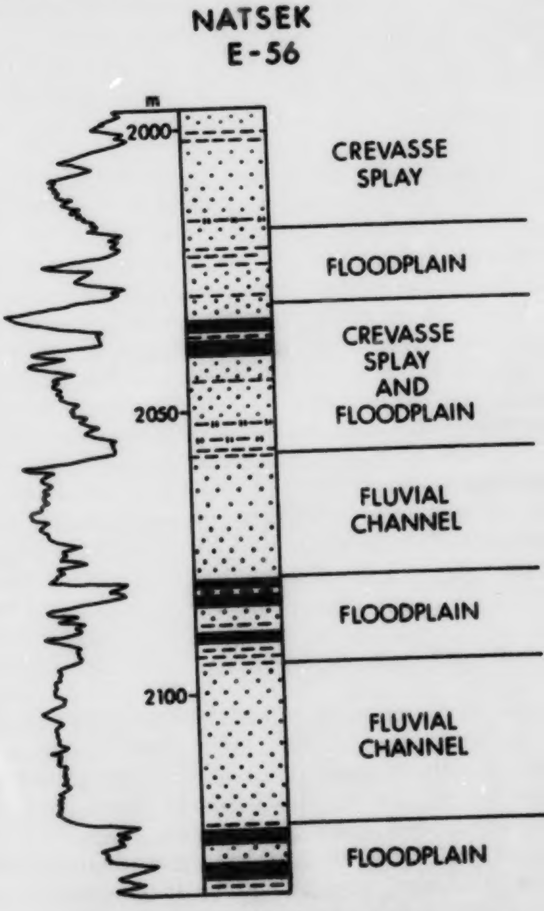


Figure 25. Upper delta plain facies; gamma-ray log trace and lithology (Natsek E-56). Aklak Sequence.

Distal delta front

The distal delta front facies includes only those beds deposited in the marine realm. For the most part they consist of stacked, coarsening-upward units, but unlike the lower delta plain and delta front facies, they are generally less than 100 m thick (Fig. 27). The basal beds are prodelta shale and siltstone that grade up into thin interbeds of shale and sandstone of the distal delta front, in turn overlain by more proximal, sandstone-dominant delta front beds that may include distributary mouth-bar and shoreface deposits. Cores in

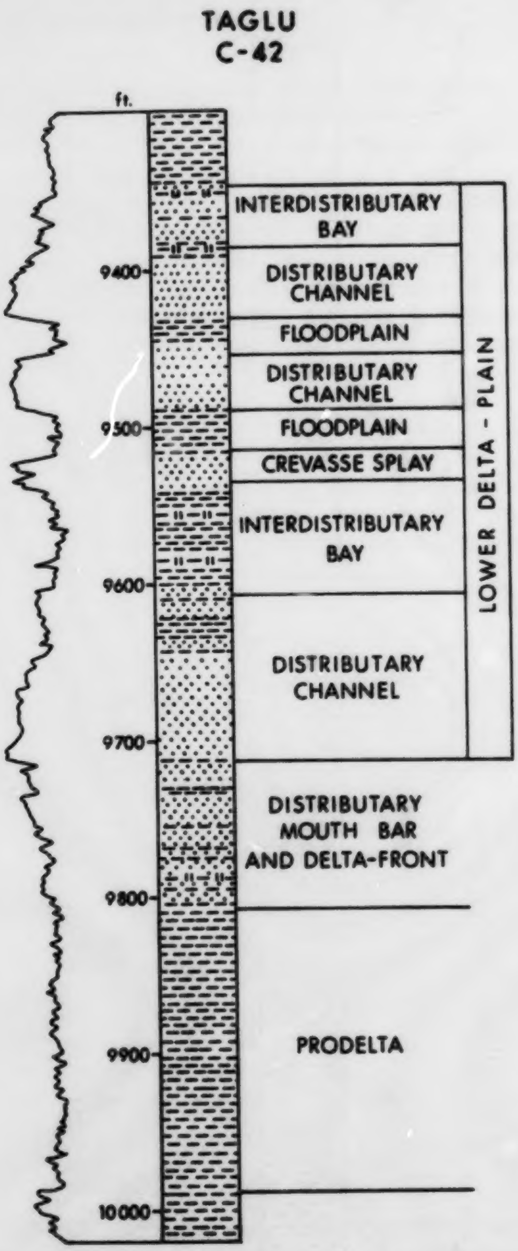
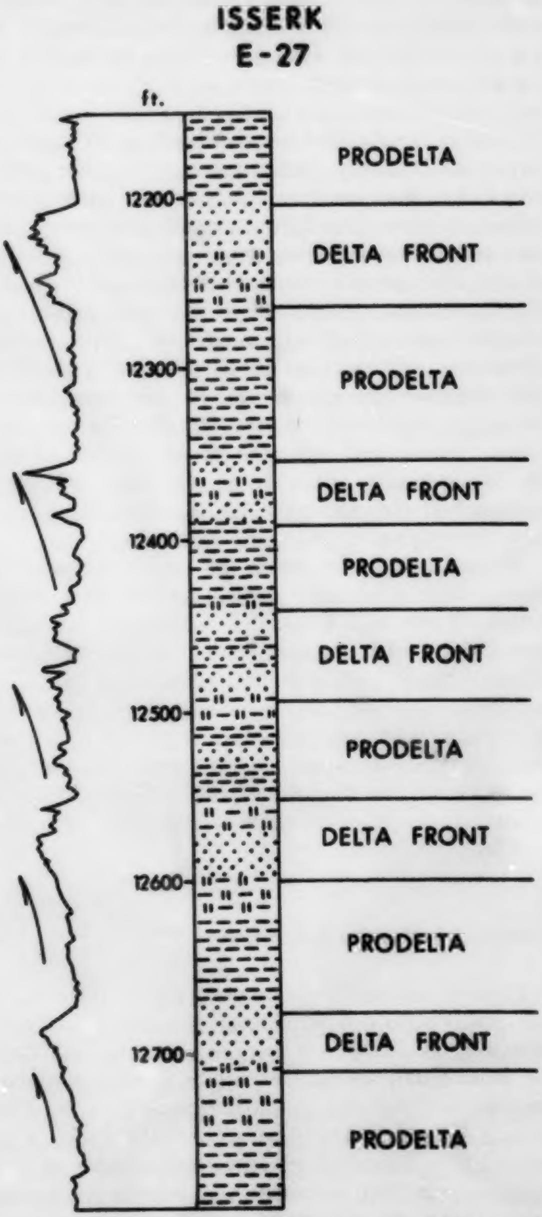

TAGLU
C-42
ft.
9400
9500
9600
9700
9800
9900
10000
INTERDISTRIBUTARY BAY
DISTRIBUTARY CHANNEL
FLOODPLAIN
DISTRIBUTARY CHANNEL
FLOODPLAIN
CREVASSE SPLAY
INTERDISTRIBUTARY BAY
DISTRIBUTARY CHANNEL
LOWER DELTA - PLAIN
DISTRIBUTARY MOUTH BAR AND DELTA-FRONT
PRODELTA

Figure 26. Lower delta plain and delta front facies; gamma-ray log trace and lithology (Taglu C-42). Taglu Sequence.


ISSERK
E-27
ft.
12200
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PRODELTA
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DELTA FRONT
PRODELTA

Figure 27. Distal delta front facies; gamma-ray log trace and lithology (Isserk E-27). Note succession of coarsening-upward cycles (arrows). Kugmallit Sequence.

this subfacies have been cut in the Issungnak 2O-61 (cores 1 to 17) and Itiyok I-27 (cores 1 to 8) wells, within the Kugmallit Sequence. Sedimentary structures within the beds from these cored intervals are scarce. Most sandstones and shales are without any apparent structures. Where structures are present, subhorizontal and ripple laminae are prevalent. Burrows and burrow mottled beds also are present. Soft-sediment deformation is a common feature of thinly bedded, distal, delta front strata. Sandstones are mostly very fine to fine grained. Examples of this facies type are not known in outcrop.

Most occurrences of distal delta front deposits are present as vertically repeated successions, alternating with thin to thick prodelta shale intervals. However, in at least one example, in the Kugmallit Sequence of the Tarsiut area, several sandy zones occur isolated within a thick succession of prodelta/shelf shale (Figs. 21, 28). These sandy zones are 40 to 70 m thick and consist of thin sandstone beds (a few millimetres to a few tens of centimetres thick) interbedded with thicker shale beds. On reflection seismic some of these zones contain low-angle, shingled clinoforms (Fig. 18). The lithology, general setting and reflection character indicate that the sandy zones are distal delta front sediments deposited at the extreme toe of the delta front.

Fluviodeltaic sediments in the Beaufort-Mackenzie Basin, most commonly present in the Fish River, Aklak, Taglu and Kugmallit sequences, are characterized by relatively continuous, parallel reflections of moderate to high amplitude (Figs. 4, 9, 29). High amplitude reflections are most common in coal-bearing delta plain successions (e.g., the Aklak and Fish River sequences; Fig. 4). Local features within fluviodeltaic sections (e.g., fluvial channels) are difficult to identify seismically because of the low resolution of most profiles.

Prodelta/shelf facies assemblage

Prodelta and shelf environments are contiguous and not readily separated. In general, prodelta deposits are intimately associated with a delta complex and form the most distal, submarine part of a delta platform, whereas shelf deposits are more remote from the delta source. Shale is the dominant rock type, with subordinate amounts of siltstone, sandstone and conglomerate. Thin carbonate beds may be present but these are usually the product of diagenesis, and not biogenic in origin. Burrows and burrow mottling are common sedimentary structures in all lithotypes. Siltstone and sandstone beds tend to be a few

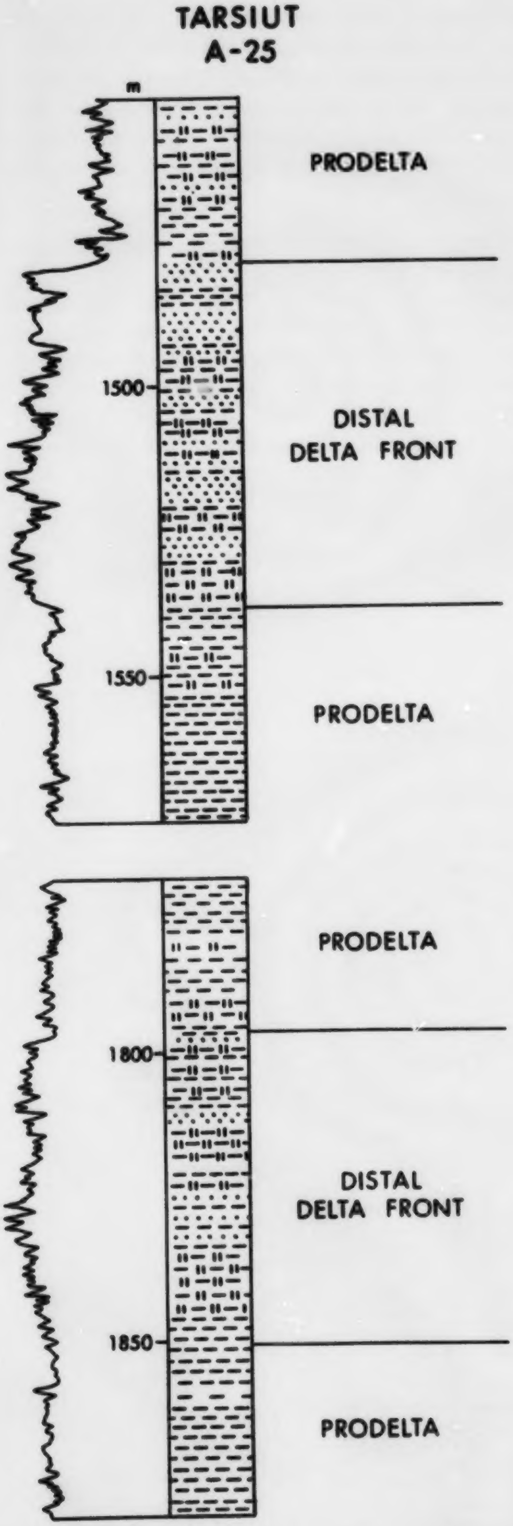


Figure 28. (Left) Prodelta/shelf deposits containing isolated sandy intervals of distal, submarine delta front deposits; gamma-ray log trace and lithology (Tarsiut A-25). Kugmallit Sequence.

millimetres to a few centimetres thick, although thicker beds may occur. If not extensively bioturbated then the siltstone and sandstone beds may be massive appearing or contain fine, subparallel laminae and ripple laminae. Conglomerate beds in shales of the Richards Sequence under Mackenzie Delta have been interpreted as submarine debris-flow deposits (Glaister and Hopkins, 1974). Although the prodelta/shelf setting of the Richards shale is probable, it cannot be ruled out that the conglomerates were deposited on a delta front slope.

Within the prodelta/shelf facies there is a distinct subfacies comprising organic-rich shales that are known only from the Boundary Creek and Smoking Hills sequences. This subfacies consists of fissile, commonly paper-thin, shale, interbedded with bentonite. Within the subsurface occurrence of the Smoking Hills Sequence, organic-rich shale intervals alternate with less organic-rich shale. During the Late Cretaceous these two sequences were deposited far from the main source of coarse clastic sediment (Dixon, 1986), on what has been interpreted as mid to outer shelf but which may have extended to the slope environment.

Prodelta/shelf successions have a typical flat SP/gamma-ray log response with spikes and leftward deflections of the trace where siltstone and sandstone beds occur. Some shales of the Smoking Hills Sequence give high gamma-ray readings. Similar organic-rich beds of the Boundary Creek Sequence have a 'normal' gamma-ray response in the Fish River B-60 and nearby wells. It is possible that the high levels of radioactivity reflect the presence of thick bentonite beds, such as are present in some outcrops of the Smoking Hills Sequence, rather than organic content. However, there does appear to be a higher carbon content in the more radioactive shales of the Smoking Hills Sequence (Myhr, 1975; Myhr and Barefoot, 1976) under Tuktoyaktuk Peninsula.

The prodelta/shelf facies assemblage is characterized seismically by parallel to slightly divergent reflections of variable amplitude and

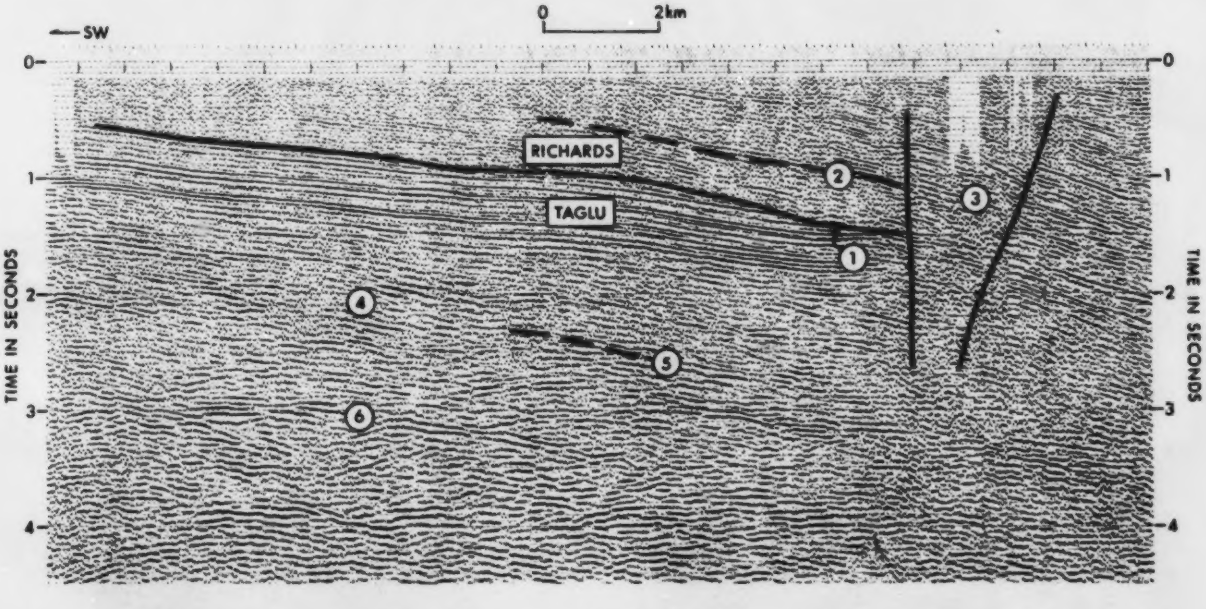


Figure 29. Reflection seismic profile across eastern Richards Island. Location shown on Figure 1. 1: truncation at the Richards/Taglu contact; 2: approximate Richards/Kugmallit contact; 3: fault zone; 4: low-angle clinoforms in lower Taglu Sequence; 5: approximate Taglu/Aklak contact; 6: probable Lower Cretaceous strata. Seismic profile from COGLA report 025 06 07 027.

continuity. Low amplitude reflection intervals are typical of clay-rich shale sections (e.g., Akpak Sequence in Figures 6 and 10). Moderate to high amplitude reflections also occur in shelf facies as a result of vertical variations in silt, sand and (diagenetic) carbonate content in the shelf sediments (e.g., Mackenzie Bay and Iperk sequences in Figures 6, 10 and 18). In the Beaufort-Mackenzie Basin, the moderate to high amplitude reflections of the shelf facies appear similar to those of a fluviodeltaic facies. Differentiation between the two is difficult on the basis of seismic character alone.

Deep water facies assemblage

Deep water sediments are those deposited on the continental slope, slope aprons, submarine canyons and fans, and basin plain. In the Beaufort-Mackenzie Basin such sediments are shale dominant and generally contain less than 30 per cent sandstone. Although no wells have penetrated Upper Cretaceous to Holocene deep water sediments in the Banks Island area, reflection seismic profiles suggest that similar facies occur in the offshore areas. Identification of deep water deposits is based principally on seismic reflection character and relative position within the total basin setting. The continental slope facies is one of the most seismically distinct facies in the basin. Continental slope clinoforms occur in parts of most sequences, with the most pronounced clinoform images occurring in the upper Tertiary section (the Kugmallit, Mackenzie Bay, Akpak and Iperk sequences; Figs. 6, 10, 30). The clinoforms (slope beds) separate topset (shelf or deltaic strata) from bottomset (submarine fan and basin plain) deposits. The seismic clinoforms indicate that 500 to 1000 m of paleobathymetric relief typically separate topset from bottomset strata. The clinoforms have variable geometry, with sigmoid configurations occurring commonly in the shale-dominant sequences (e.g., Mackenzie Bay and Akpak), and more complex, sigmoid-oblique configurations occurring in the sandier sequences (e.g., Iperk). Local paleoslope features such as slumps and debris flows are common and appear seismically as hummocky and lens-shaped discontinuous reflections (e.g., Figs. 6, 7). Clinoforms occur in the older, pre-Kugmallit sequences in the eastern, and less commonly, in the central parts of the area

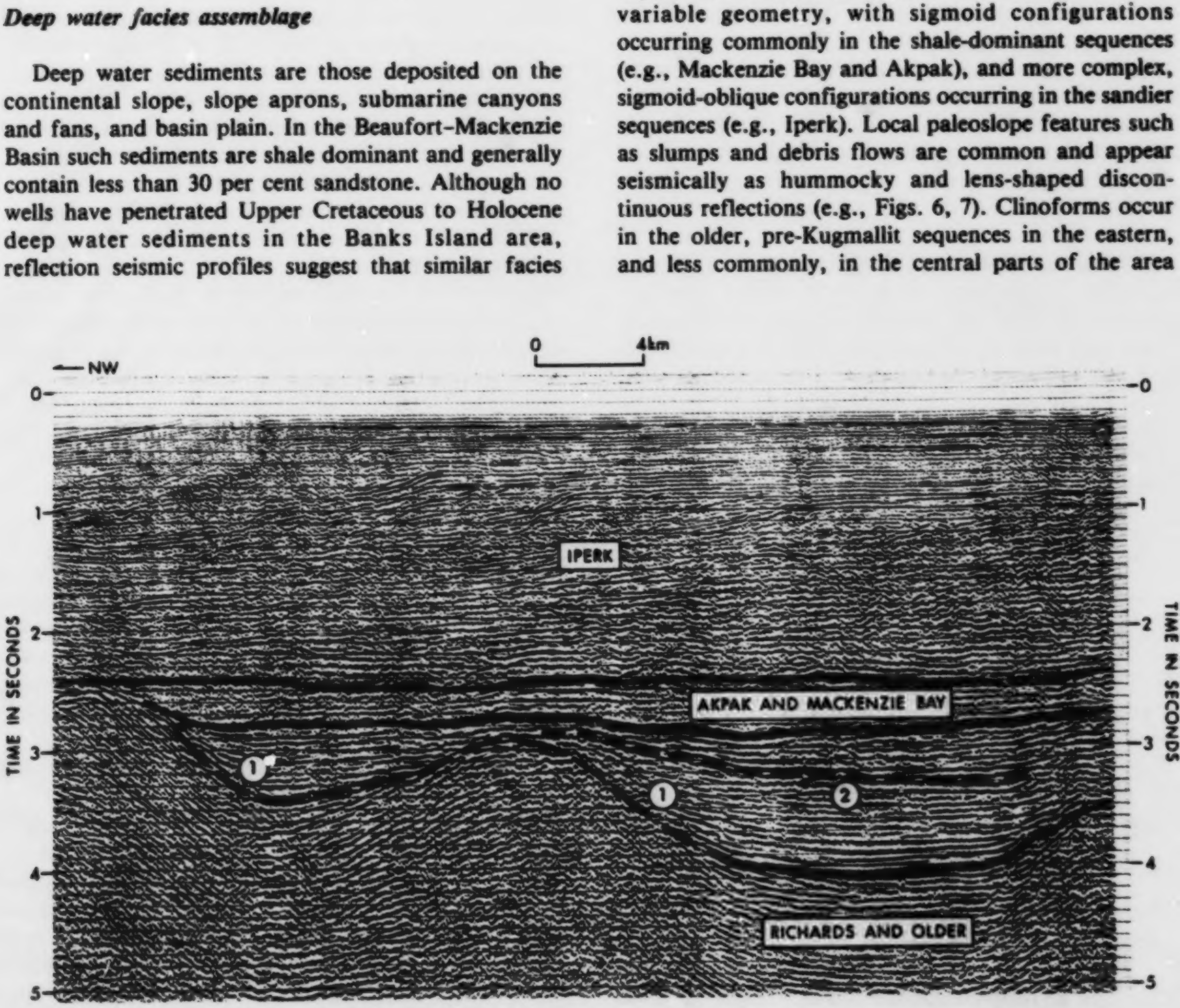


Figure 30. *Reflection seismic profile across the north-central Beaufort shelf. Location shown on Figure 1. 1: onlap of Kugmallit submarine fan deposits onto anticline flanks; 2: downlap of Kugmallit deep water deposits of the progradational depositional phase onto Kugmallit submarine fan strata. Seismic profile from COGLA report 005 09 08 044.*

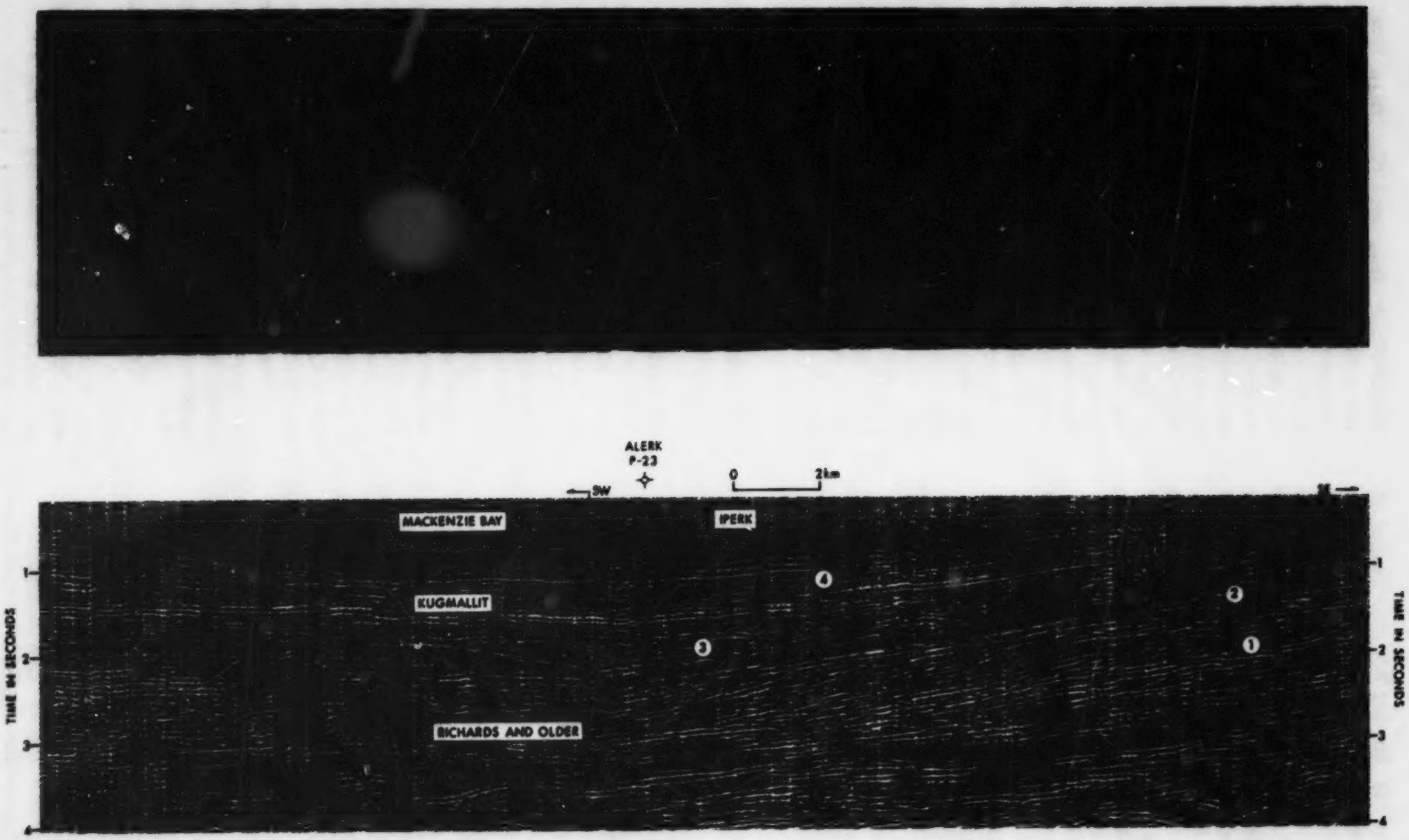


Figure 31. Reflection seismic profile through the Alerk P-23 well. Location shown on Figure 1. 1: clinoforms in the Taglu and/or Aklak sequences; 2: truncation of (?)Richards strata at sub-Kugmallit submarine unconformity; 3: slope and submarine canyon-fill deposits in the Kugmallit Sequence; 4: fluviodeltaic deposits in the Kugmallit Sequence. Seismic profile from COGLA report 07 09 08 353.

(e.g., Figs. 7, 25, 31), but are not well imaged on seismic profiles crossing the highly deformed central and western Beaufort–Mackenzie Basin. In the absence of seismically imaged slope clinoforms the interpretation of deep water facies in the older and more deeply buried sequences is based on relative basin position. Few wells have penetrated the deep water facies of the Taglu, Aklak and Fish River sequences, although some of the shales of the the Tent Island Formation (basal part of the Fish River Sequence), exposed in the northern Richardson Mountains, are probably slope deposits.

Known slope deposits have been drilled in the Iperk Sequence, in wells such as Nektoralik K-59 (Dixon and Snowdon, 1979), Kopanoar M-13 (Dixon et al., 1984), Nerlerk M-98, and Koakoak O-22. These deposits are predominantly shale with thin interbeds of siltstone and sandstone. Silt, sand and pebbles are a common component of the cuttings, but the SP/gamma-ray logs rarely indicate the presence of thick sandstone beds. In the Iperk Sequence, carbonate material, of presumed diagenetic origin (Dixon et al., 1982), is a common component of the shales.

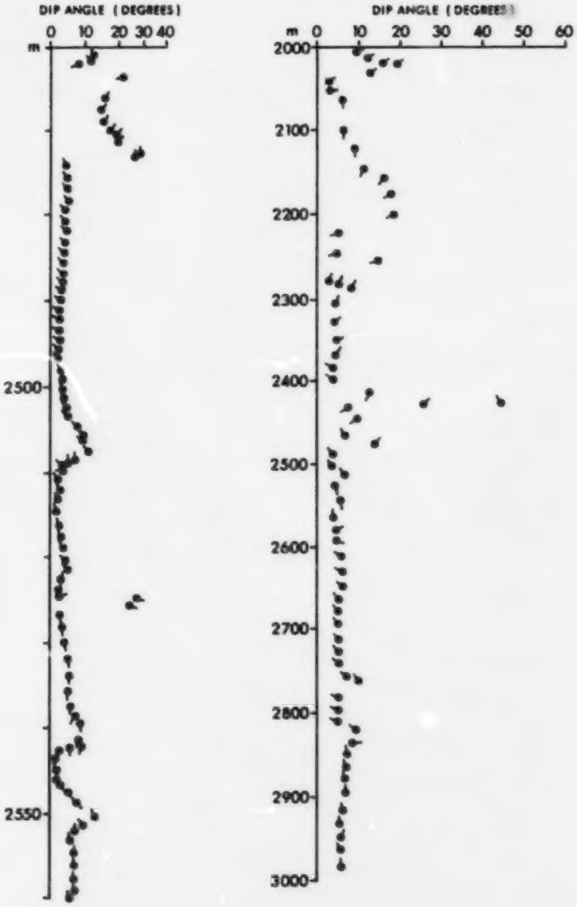


Figure 32. Dipmeter log through submarine-canyon deposits of the Kugmallit Sequence; Alerk P-23.

It is presumed that slope-apron deposits may develop when a delta progrades to near the shelf edge and coarse clastic sediment can be fed directly down the continental slope. Such a scenario appears to have developed during the later stages of Kugmallit delta deposition. These Kugmallit base-of-slope deposits are shale-dominant with a considerable amount of thinly interbedded siltstone and sandstone. Such deposits commonly have seismic reflection configurations similar to submarine fan deposits, although they may not show the same complexity of hummocky reflections. No cores have been recovered in possible apron deposits, so the fabric of the sediments is unknown, although one can conjecture that if they are apron deposits they were deposited as slumps, slides, turbidity currents, and as pelagic sediments.

Submarine fan and canyon-fill deposits have been interpreted as being present at the base of the Fish River Sequence (Cuesta Creek strata; Dixon, 1988), in the Taglu Sequence at Edlok N-56 (Dietrich et al., 1989), in part of the Kugmallit Sequence (Dixon et al., 1984), and in the Iperk Sequence. The interpretations are based on facies associations, log trace patterns, seismic facies characteristics and basin position. Also, it can be demonstrated from seismic data that prior to Kugmallit deposition there was a period of erosion of the continental slope and shelf, probably due to a major sea-level drop. Such conditions would be suitable for the formation of major submarine fans. The only identifiable submarine canyon deposits penetrated by a well are in the basal part of the Kugmallit Sequence of the Alerk P-23 well (Fig. 31). The canyon-fill sediments in the Alerk P-23 well are mostly shale, but within the succession there is at least one conglomerate interval that was cored (cores 4 and 5). Canyon-fill deposits in core 3 from the Alerk well consist of finely laminated silty to sandy shale with occurrences of overturned bedding due to slumping. The conglomerate in cores 4 and 5 is matrix supported and consists of chert, sandstone and shale clasts in a sand to granule matrix. On the dipmeter log the canyon fill sediments can be divided into thick intervals with similar dip values and direction (Fig. 32). These are interpreted as representing sediment lobes filling the canyon from slightly different directions. Reflection seismic data tend to confirm this interpretation; it can be seen that there are wedge-like and hummocky intervals (Fig. 31), suggesting prograding and overlapping depositional lobes.

Shale and siltstone are the dominant lithotypes in submarine fan deposits, but scattered throughout are sandstone-dominant intervals up to 300 m thick. Local conglomeratic beds also may be present. Sandstone intervals in the Kopanoar M-13 well have the following features (Fig. 33):

1. They tend to have an overall fining- and thinning-upward trend.
2. Shale interbeds increase in number and thickness upsection.
3. The lowest, and generally thickest, sandstone unit within the fining-upward interval usually has an abrupt basal contact.

Such deposits were described and interpreted as channel deposits on a submarine fan (Dixon et al., 1984). Seismically, the submarine fan deposits are characterized, in strike view, by hummocky and mounded reflections exhibiting complex lateral variations in continuity and amplitude. The mounded seismic facies (Fig. 34) are interpreted as coalescing and overlapping channel and levee deposits on the inner and middle portions of large-scale fans. Basinward, the outer fan and basin plain sediments are characterized by more continuous, subparallel reflections (Fig. 35). These lithological and seismic

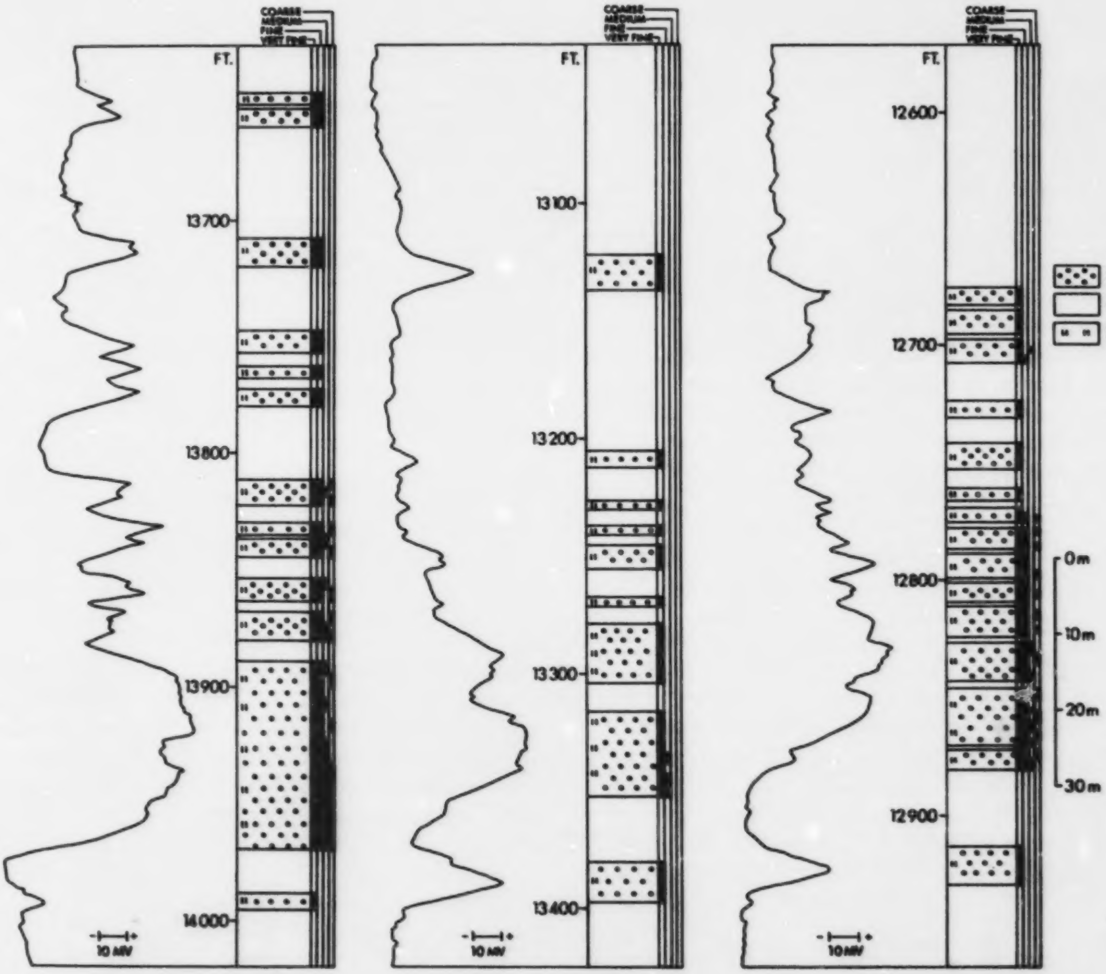
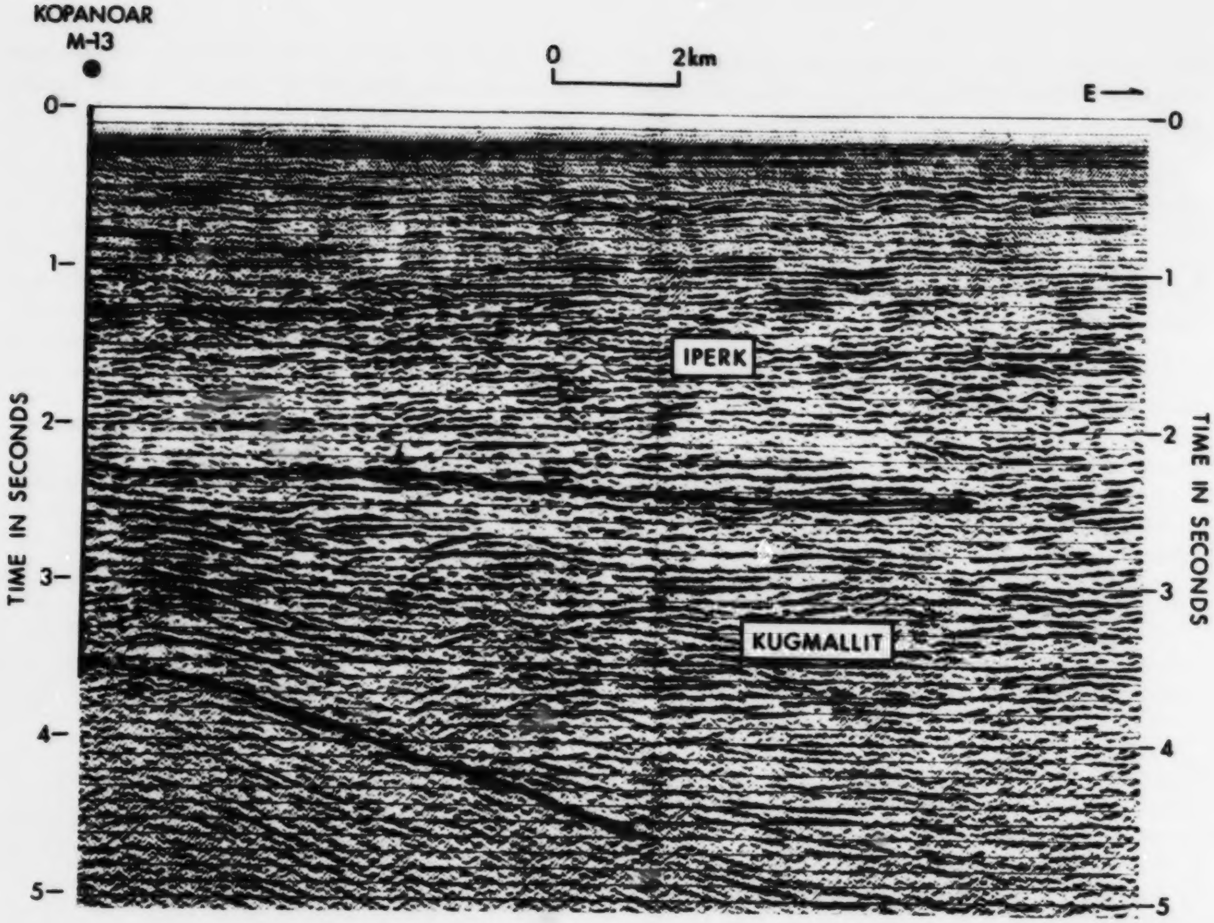


Figure 33. Submarine fan deposits of the Kugmallit Sequence; SP log trace (inverted) and lithology (Kopanoar M-13).


KOPANOAR
M-13
0
2km
E
IPERK
KUGMALLIT
TIME IN SECONDS
0
1
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4
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TIME IN SECONDS
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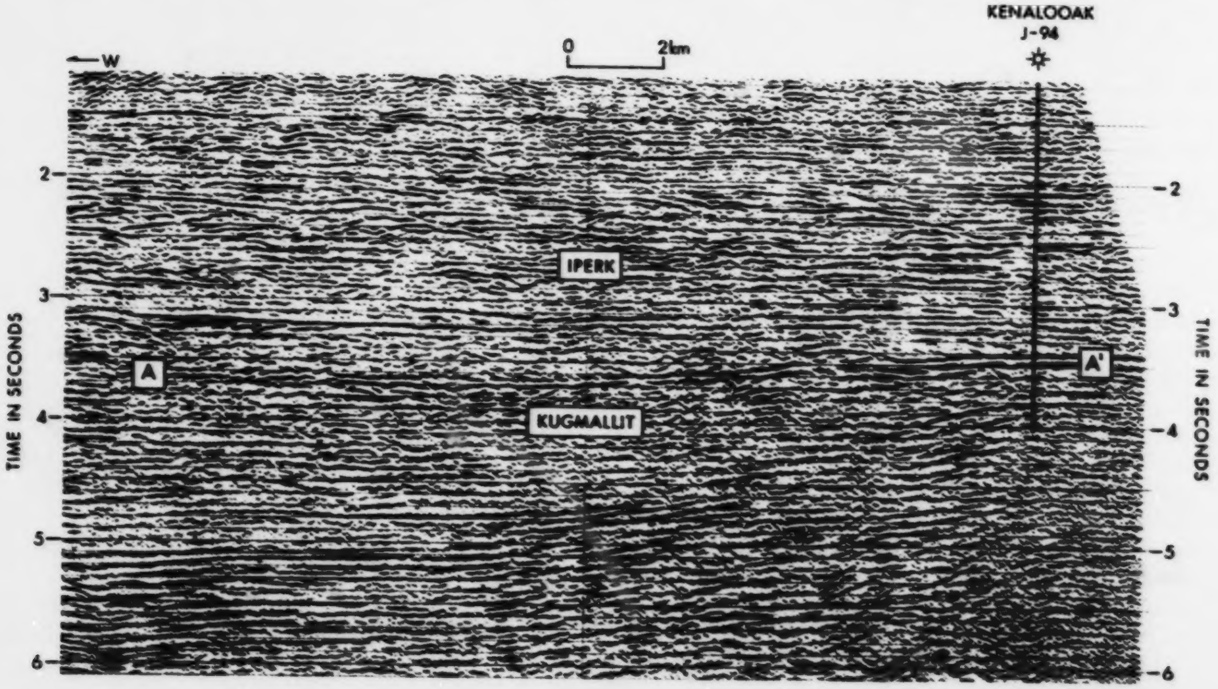
KENALOOAK
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TIME IN SECONDS
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characteristics are similar to those described in detail by Heritier et al. (1979, 1981) for Lower Eocene submarine fan channel and levee deposits of the Frigg field in the North Sea. Cores have not been cut in any of the channel deposits; consequently, details of the internal stratification and bed thicknesses are not known.

At Edlok N-56, between log depths 1736 and 2281 m, there is a relatively continuous succession of sandstone abruptly overlain and underlain by shale. Gamma-ray log response is blocky, indicating thick, sand-rich units separated by thin, mud-rich beds (see the log in Figure 22A). The sandstones are mostly very fine to fine grained, with commonly occurring coarser material, up to small-pebble grade, in the cuttings. Reflections within this unit are mounded and onlap onto adjacent slope clinoform reflections (Fig. 4).

Figure 34. Strike oriented reflection seismic profile through the Kopanoar M-13 well, illustrating hummocky, discontinuous reflections in inner and middle submarine fan deposits of the Kugmallit Sequence. Location shown on Figure 1. Seismic profile from COGLA report 005 09 08 0100.

The bulk of the known fan deposits consist of shale and siltstone. A few cores have been cut in these rock types; for example, from the Aiverk 2I-45, Koakoak O-22, Kopanoar 2I-44, and Uviluk P-66 wells. The strata in these cores consist of dark grey to black shale interbedded with numerous thin laminae and beds of siltstone and very fine grained sandstone. The siltstone and sandstone beds are usually a few millimetres to a few centimentres thick, and rarely exceed 10 cm. Current ripple laminae are common, and load structures may be present. In the Uviluk P-66 core (core #1) there is also a 20 to 30 cm thick bed of conglomerate. The clasts are subrounded shale in a mud matrix. Shale beds are interpreted as interchannel and/or levee deposits with some scattered debris flow deposits. Toward the outer fan, shale and siltstone form 80 to 90 per cent of the succession, although isolated sandstone bodies, presumably of channel origin, can extend into the outer fan (e.g., the gas-bearing sandstone unit in the Kenalooak J-94 well).

Basin plain sediments are interpreted from reflection seismic character and their basinal position. Hummocky reflections of the inner and middle fan merge basinward into subparallel to parallel, generally continuous reflections of the outer fan and basin plain. The Nektoralik K-59 well penetrated basin plain sediments, and the Kenalooak J-94 well penetrated outer fan and possibly innermost basin plain sediments (Fig. 35). If the sediments in the K-59 and J-94 wells are typical of the basin plain, then shale and siltstone are prevalent.

Figure 35. Strike oriented reflection seismic profile through the Kenalooak J-94 well, illustrating subparallel reflections of lower submarine fan and basin plain deposits in lower Iperk, Kugmallit and older sequences. Location shown on Figure 1. A–A', sub-Iperk unconformity. Seismic profile from COGLA report 005 09 08 0100.

The types of deep water deposits that formed in the Tertiary sequences appear to be related to relative sea-level changes and the rate of sedimentation. Submarine fan deposits formed primarily during large, relative drops in sea level, when shelf-edge erosion and canyon formation was active, and there was a narrow shelf on which limited amounts of sediment could accumulate. During relative sea-level highstands, a wide shelf existed and much of the coarse sediment was trapped in deltas. If sedimentation and basin subsidence kept pace, the tendency was for the delta depocentre to remain at the basin margin (e.g., during Mackenzie Bay and Akpak deposition), and for the shelf, slope and basinal deposits to be very muddy. If sedimentation rates exceeded basin subsidence and relative rise in sea level, then the delta tended to build outward to the shelf edge, allowing coarse sediment to be available for resedimentation into deeper water as possible slope-apron sands. This latter situation appears to have occurred during parts of Kugmallit and Iperk deposition.

DESCRIPTION OF SEQUENCES

Boundary Creek Sequence

Description and distribution

Strata comprising the Boundary Creek Sequence are the same as those of the formally defined Boundary Creek Formation and consist of the known exposed strata in the northern Yukon and its subsurface equivalents. The type section of the formation is located in the Boundary Creek valley, a western tributary of Fish River, northern Richardson Mountains (Fig. 1; Young, 1975). The nearby Fish River B-60 well contains Boundary Creek strata between log depths 2198.8 and 2430.5 m (7214-7974 ft., Fig. 21). At the type locality, Boundary Creek strata rest abruptly on iron-rich Albian shales of the Rapid Creek Formation and are erosionally overlain by clastics of the Cuesta Creek Member, Tent Island Formation (which are the basal beds of the Fish River Sequence).

In outcrop, Boundary Creek strata are distinct, consisting of light-grey weathering shale that is black when wet or on fresh surfaces (Fig. 36). It is soft and very thin bedded, resulting in paper-thin partings. Interbedded throughout the unit are bentonite beds a few millimetres to a few centimetres thick, which weather yellow or orange. Ironstone concretions are a common component of the sequence, usually occurring in distinct bands. Centimetre-thick beds of siltstone are scattered throughout the unit. Selenite crystals, present on outcrops, are the product of surficial weathering, presumably through the oxidation of pyrite and the resulting release of sulphur. The shales are rich in organic carbon, which averages between 2 and 4 per cent, but may be as high as 7 per cent (unpublished results from samples collected at the type section, L.R. Snowdon, pers. comm., 1984). Young (1975) also noted the presence of thin calcarenite beds. Syndepositional folds are present in the type area and range from simple antiforms (Fig. 14) with subvertical axes to recumbent folds with horizontal axes.

The Fish River B-60 well (Fig. 21), in close proximity to the type area, will be used as a reference well for the subsurface characteristics of the sequence. There, the Boundary Creek Sequence consists of a monotonous succession of dark grey to black fissile shale. Because the bentonite beds are very thin, the gamma-ray log does not reflect any high levels of radioactivity. Consequently, the log trace is typical of a 'normal' shale (Fig. 37).

Boundary Creek strata also are present in the vicinity of the informally named "Treeless Creek", a few kilometres east of Mount Lang in the northern Richardson Mountains (Jeletzky, 1960 – informally called the "Upper Cretaceous shale division"). There, the surface weathering has created some bright orange weathering bands. Jeletzky used the coloration to erect several informal members.

Correlation of the Boundary Creek Sequence into the subsurface, away from Fish River B-60, can be difficult, because of its thinness and pre-Smoking Hills erosion. The Boundary Creek Sequence cannot be differentiated seismically from overlying Smoking Hills strata. Based on log character and some palynological data from the Parsons N-10 well (Brideaux and Myhr, 1976) it would appear that there is a thin interval (1956.8-2020.8 m/6420-6630 ft.) that contains a palynoflora typical of Boundary Creek strata (D.J. McIntyre, pers. comm., 1987), and which has a more 'normal' gamma log trace than the overlying, highly radioactive Smoking Hills shale. Consequently, it is herein reinterpreted as representing a thin erosional remnant of Boundary Creek strata. This stratigraphic relationship can be traced through many of the Parsons wells, and nearby wells on Tuktoyaktuk Peninsula (Fig. 23).

Correlation of Boundary Creek strata into more basinward locales has not been possible because of a lack of deep penetration by wells and poor seismic resolution at depth. Seismic lines that cross the southern end of Kugmallit Trough indicate that

Figure 36. Typical outcrop of Boundary Creek strata in the type area. Banded appearance is due to the presence of bentonite beds and concretion horizons. View looking to the north. ISPG photo. 2428-4.

Smoking Hills and Boundary Creek strata are truncated in a basinward direction (Fig. 38). This relationship is illustrated in the Reindeer D-27 well, where Maastrichtian to Paleocene Fish River strata rest on probable Albian beds. A similar erosional relationship is seen on reflection seismic profiles in the vicinity of the Kilannak A-77 well near Amundsen Gulf. The basinward truncation of Upper Cretaceous strata suggests the absence of the Boundary Creek Sequence under much of the Beaufort shelf. Its distribution under the western Beaufort shelf remains speculative.

Thicknesses of the Boundary Creek Sequence range from a reported 1100 m (Young, 1975) at Cuesta Creek to a few tens of metres in the Parsons area. At the type area it is about 250 m thick. However, it has been noted that there are large, recumbent folds in some outcrops, which will give a false thickness if not restored to horizontal.

There do not appear to be any equivalent strata on Banks Island, and this may also be the case for the offshore Banks Island area. Although Miall (1979) reported a Cenomanian–Turonian age for the basal Kanguk Formation in the Storkerson Bay A-15 well, which would imply an age-equivalence to Boundary Creek strata, the oldest age Miall indicates elsewhere for the Kanguk Formation is late Santonian. Furthermore, the Cenomanian–Turonian age was based upon isolated occurrences of *Haplophragmoides bonanzensis*, which by itself is not wholly age-diagnostic of the Cenomanian–Turonian (J.H. Wall, pers. comm., 1987).

Depositional environments

The lack of coarse detritus indicates a generally low-energy depositional environment, and the abundant organic carbon and pyrite in the shales suggests that

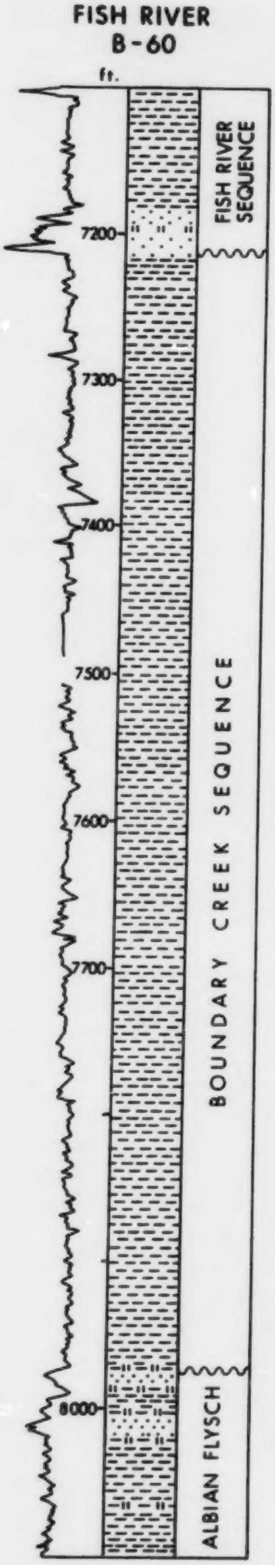

Figure 37. Gamma-ray log trace and lithology of Boundary Creek strata in Fish River B-60 well.

low oxygen conditions were common during and immediately after deposition. Coarser grained, lateral equivalents of the Boundary Creek Sequence are present 200 km to the south, under Eagle Plain, in the Parkin and Fishing Branch formations (Dixon, in press b). There, the equivalent strata are marine shelf deposits. The basinward position of Boundary Creek strata and their lithological character indicate deposition on the outer shelf to slope. The common occurrence of large, gravity-slide, syndepositional folds also indicates an outer shelf to slope environment.

Age and correlation

The Boundary Creek Sequence at its type area contains an abundant and distinct palynoflora (McIntyre, 1985) that indicates a Cenomanian to Turonian age. Jeletzky (1960) reported ammonites and pelecypods from the "Treeless Creek" area, indicative of a similar age. Foraminifers, radiolarians and fragments of vertebrate fossils are scarce and generally present only in the upper part of the sequence (Young, 1975). Chamney (1972), in a preliminary report on foraminifers from the Boundary Creek area, compared the fauna with that recovered from the Smoking Hills Formation on Anderson Plain and inferred that the Boundary Creek Formation/Sequence must be as young as Campanian. However, it should be pointed out that the much more abundant pollens, spores and dinoflagellates do not indicate an age younger than Turonian. The apparent lithological similarity between the Smoking Hills and Boundary Creek successions and their similar foraminiferal assemblages (at the generic level) suggested to some earlier workers that they were correlative (Chamney, 1972; Young, 1975; Young et al. 1976). There are, however, sufficient differences in the ages of the floral assemblages, lithological attributes, and stratal distribution to suggest that they are two separate sequences.

Strata equivalent to the Boundary Creek Sequence in northern Yukon include the lower part of the Monster Formation (Ricketts, 1988), and the Parkin and Fishing Branch formations of Eagle Plain (Dixon, in press b). Some of the fault-bounded outcrops along Porcupine River, in the Old Crow Basin, have been dated as Cenomanian-Turonian (Norris, 1981e) and consist of marine sandstone, siltstone and shale (Dixon, op. cit.). In northern Alaska the Seabee Formation, lowermost shales of the Colville Group (Molenaar, 1983), and the Hue Shale (Bird and Molenaar, 1987) contain some age-quivalent strata.

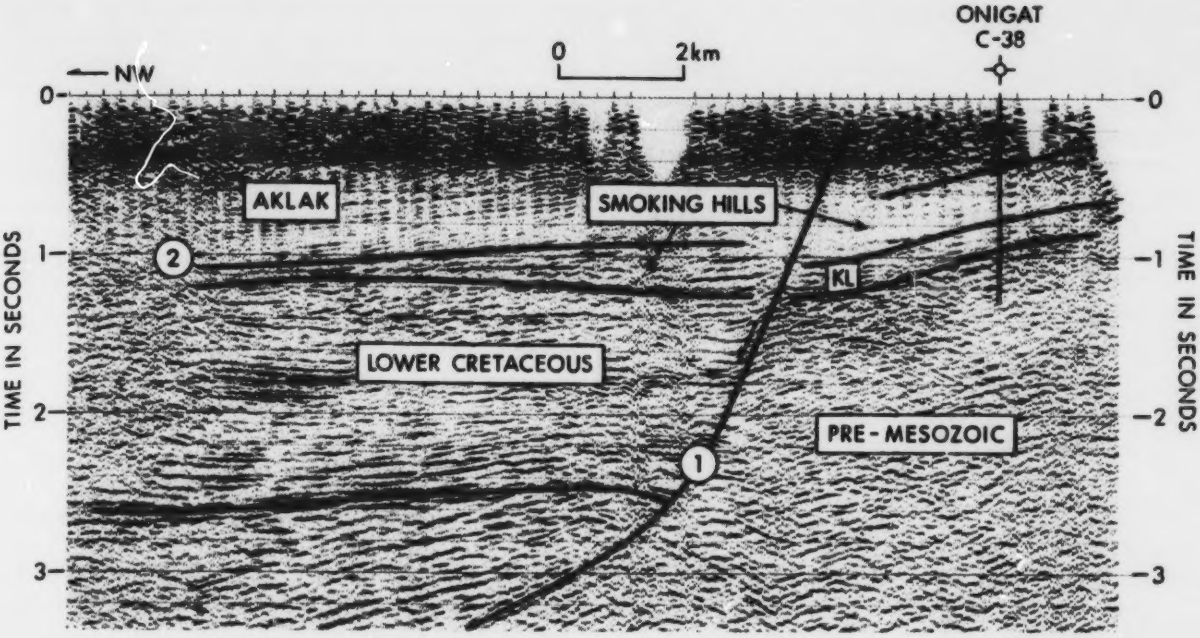

Figure 38. Reflection seismic profile across southeastern Tuktoyaktuk Peninsula. Location shown on Figure 1. 1: Eskimo Lakes Fault; 2: basinward truncation and thinning of Smoking Hills strata below sub-Aklak unconformity. Seismic profile from COGLA report 528 09 08 01.

Smoking Hills Sequence

Description and distribution

The Smoking Hills Sequence is named after the Smoking Hills Formation, to which it is equivalent. The formation has its type section along Horton River, east of Mackenzie Delta (Yorath et al., 1975). There, and throughout its known surface occurrence, it consists of dark grey to black, thinly bedded shale. Yellow to orange weathering bentonite beds are very common, and, unlike those of the Boundary Creek Formation, they can be present as amalgamated intervals up to 1 m thick (for example, along the cutbanks of Kugaluk River, east of Mackenzie Delta). A characteristic of the Smoking Hills Formation is its combustible nature along the sea cliffs of Franklin Bay (Matthews and Bustin, 1984).

At the type area, the Smoking Hills Formation may be divided into three distinct units, based on the colour of their weathered surfaces (Fig. 39): a lower, dark grey to black weathering unit; a middle, lighter grey weathering interval; and an upper unit similar to the lower. The organic carbon content of the three divisions also varies; the middle unit has a consistently higher carbon content than the other two units (Table 1). Minor mineralogical differences have been noted between the three units (Table 2), principally in the different concentrations of expandable and/or mixed layer clays, and less dramatically in the zeolite content.

Yorath et al. (1975) reported the presence of locally occurring basal conglomerates along Horton River. One of these locations was re-examined in 1984 (unpublished data of Dixon and McIntyre) and it appeared that the conglomerates were much younger river-terrace gravels, related to Pleistocene or Holocene deposition. Outside Anderson Basin the only other known outcrops occur at the southern end of Caribou Hills along Douglas Creek, and a few kilometres west of Sitidgi Lake along Norris Creek (both areas were originally mapped as Tent Island Formation by Norris, 1981d). At these two locations the Smoking Hills Sequence tends to be lighter grey weathering, thicker than in Anderson Plains, and tends to contain bands of cone-in-cone limestone.

In the type area, Smoking Hills strata rest abruptly on the Albian Horton River Formation. In the Sitidgi Lake–Caribou Hills area vegetation hides the lower

TABLE 1

Rock-Eval analysis of organic carbon content of samples from the Smoking Hills Formation/Sequence along Horton River (illustrated in Fig. 37). Analyses supplied by L.R. Snowdon, Geological Survey of Canada. Samples were collected by D.J. McIntyre (Field sample code: MDB, field officer's code; 84, year collected; 12, section number; 3 to 15, sample numbers). Sample spacing, approximately 2 m.

Sample No.	TOC
Upper unit	
MDB84-12-15	11.7
MDB84-12-14	1.4
MDB84-12-13	6.6
MDB84-12-12	5.4
Middle unit	
MDB84-12-11	7.3
MDB84-12-10	9.1
MDB84-12-9	9.6
Lower unit	
MDB84-12-8	5.7
MDB84-12-7	3.9
MDB84-12-6	3.4
MDB84-12-5	5.0
MDB84-12-4	7.6
MDB84-12-3	2.9

contact but mapping (Norris, 1981d), and the known Cretaceous geology in the nearby Inuvik D-54 well, indicate that Smoking Hills shale rests on Albian shale. Overlying strata along Horton River are light grey shales of the Mason River Formation (part of the Fish River Sequence). The Mason River shale is in abrupt contact with Smoking Hills strata (Fig. 39). At Caribou Hills, the Reindeer Formation (Aklak Sequence) rests abruptly and erosionally on Smoking Hills shale.

The nearest wells to the type area that contain Smoking Hills Formation are the Kiligvak I-16 and Amaguk H-29 wells on Tuktoyaktuk Peninsula. At both locations the succession consists of dark grey to black shale with minor amounts of siltstone and some thin carbonate beds (presumably concretion or cone-in-cone layers). The gamma-ray log has a distinct, high, radioactive reading, long recognized as a useful marker interval throughout the Tuktoyaktuk Peninsula and southern Mackenzie Delta (Myhr, 1975). In many of the wells on Tuktoyaktuk Peninsula, there is a succession in which there are several radioactive zones, only the lowermost of which has been correlated with the Smoking Hills Formation, and the higher zones have been placed in the Mason River Formation (Myhr, 1975). The radioactive zones reflect the presence of high concentrations of bentonite beds and their inherently higher concentration of radioactive minerals (Myhr, 1975; Myhr and Barefoot, 1976). The stratigraphy of the Smoking Hills Sequence on Tuktoyaktuk Peninsula appears to be more complex than suggested by Myhr (op. cit.). Detailed correlations of the intervals containing radioactive zones indicate that they are all part of a single sequence (Fig. 40, in pocket). The physical correlations indicate that there are onlapping relationships to local highs and perhaps internal erosion surfaces. Paleontological data are sparse but palynological data from a few wells (e.g., Tuk L-09, Parsons N-10; D.J. McIntyre, pers. comm. and internal GSC paleontological report 4-DJM-1984) favour the inclusion of all the radioactive zones within the Smoking Hills Sequence. The Mason River Formation does not contain much bentonite in its outcrop area, and strata that can be correlated with Mason River Formation in the subsurface also do not contain radioactive zones such as those seen in the interval under discussion. It would be logical to include all the radioactive zones and intervening 'normal' shales within the Smoking Hills Sequence/Formation. The Smoking Hills Sequence has a very distinct palynomorph and dinoflagellate assemblage that is helpful in identifying age-equivalent strata. Although radioactive shales are a characteristic of the Smoking Hills Sequence there are exceptions. Santonian-Campanian strata have been recognized in the Tuk L-09 well; however, the succcession in L-09 has no radioactive zone, but can be correlated on the basis of its contained fossils with the Smoking Hills Formation/Sequence.

Figure 40 illustrates the suggested correlation of Smoking Hills strata from northeast Tuktoyaktuk Peninsula to the southwest. The subdivisions (informal) seen in the Kanguk F-42 well are typical for the northeast end of Tuktoyaktuk Peninsula, but change dramatically southward. Onlap onto pre-Smoking Hills highs is apparent in the Atkinson to Pikiolik areas. Smoking Hills strata thicken southwest of the Pikiolik area. If the base of the Mason River Formation (Fish River Sequence)/top of Smoking Hills Sequence has been chosen correctly, it is evident that some low-angle regional truncation occurred prior to Fish River/Mason River deposition. Also, the fact that the Smoking Hills Sequence rests on a variety of stratigraphic units, ranging in age from early Paleozoic to Albian, indicates that there was substantial pre-Smoking Hills erosion. The westernmost known

TABLE 2

X-ray mineral identification in samples from the Smoking Hills Formation/Sequence, Horton River (illustrated in Fig. 37). Analyses by J. Wong, Geological Survey of Canada. Samples are the same as those in Table 1 (Section MDB84-12).

Sample no.	Mixed layer/ expandable clays	Illite	Kaolinite/ chlorite	Quartz	Jarosite	Feldspar	Others*
Upper unit							
15	39	12	5	37	–	4	3
14	37	11	5	34	5	5	3
13	29	9	–	37	4	4	17
12	23	14	–	45	5	4	9
Middle unit							
11	28	9	–	41	5	6	11
10	30	10	tr	38	6	4	12
9	8	6	–	28	4	–	54
Lower unit							
8	9	11	tr	51	21	–	8
7	13	9	–	36	32	–	10
6	16	9	–	35	10	–	30
5	16	11	–	46	12	–	15
4	8	9	5	42	7	4	25
3	–	–	–	8	8	6	78

*Others include: bassanite, clinoptilolite, diaspore, geothite, calcite, zeolite, and possibly amphibole and rutile.

tr = trace

Samples 4, 6, 9 are bentonitic.

Sample 3 contains 78 per cent bassanite, which is probably an alteration product of gypsum (selenite crystals are a common surface-weathering product).

occurrence of Smoking Hills strata is in Ulu A-35, a few kilometres south of Shallow Bay (log depths 1902-2185 m/6240-7169 ft., Fig. 21).

The thickness of the Smoking Hills Sequence is highly variable (Fig. 41) due to depositional thinning and erosion. Along Horton River and other outcrop areas the succession is only 30 to 100 m thick, whereas under Tuktoyaktuk Peninsula it can be in excess of 500 m. The thickest known section occurs in Nuvorak O-09, at the northeast end of the peninsula. Other locally significant, thick sections occur in the areas of the Mayogiak, Imnak, and Kugpik wells. Absence of Smoking Hills strata in Pikiolik M-26 appears to be due to pre-Aklak erosion. Erosion of the sequence from part of Tununuk High is most apparent, and, as previously noted, its absence from the southwestern end of Kugmallit Trough is readily interpreted from available reflection seismic data (Fig. 38). Farther north, beneath the eastern Beaufort shelf, Smoking Hills strata are truncated in a basinward direction below a sub-Fish River unconformity.

On Banks Island, equivalent strata appear to be the bituminous shale member (Miall, 1979) at the base of the Kanguk Formation. It is a relatively thin unit, generally less than 15 m thick, and consists of dark grey to black, organic-rich, papery shale. Thin beds (up to 21 cm) of tuff and bentonite beds are common in the bituminous shale member. The general thinness of the unit and of the included bentonite and tuff beds probably accounts for the lack of high values on the gamma-ray log in most of the wells (Storkerson Bay A-15 is an exception).

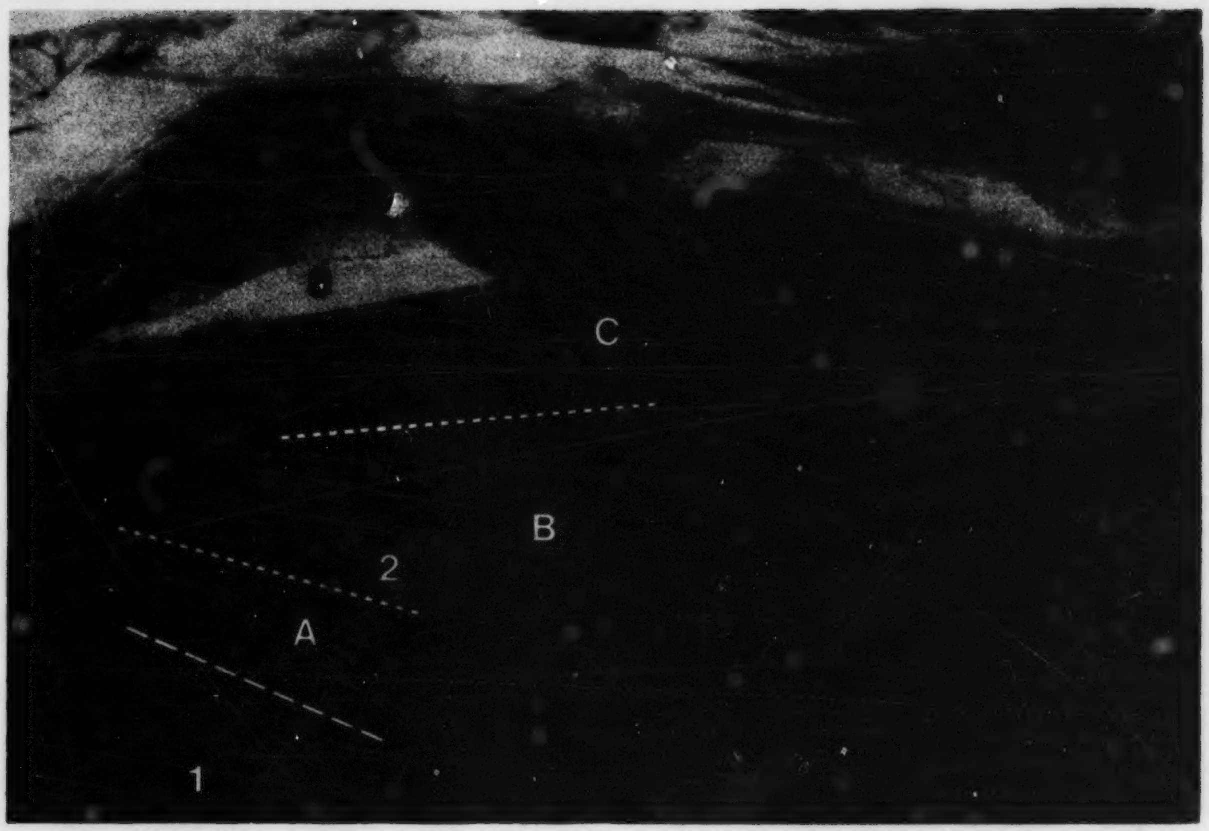

***Figure 39.** Smoking Hills (2) strata along the southwest bank of Horton River (type area). Informally designated lower (A), middle (B), and upper (C) members. Light grey material on surface of upper member is derived from overlying beds. Overlain by Mason River Formation (3) (Fish River Sequence), and underlain by Albian Horton River Formation (1). ISPG photo. 2236-3.*

Depositional environments

The Smoking Hills Sequence on Banks Island and mainland Canada has many features in common with the Boundary Creek Sequence — a lack of coarse detritus and an abundance of organic-rich, pyritic, papery shale — features indicative of a low energy, low oxygen environment. Like the Boundary Creek Sequence, an outer shelf to slope depositional setting is interpreted for the Smoking Hills Sequence. Sandier shelf-equivalents are known to the south, in the upper part of the Eagle Plain Group (Dixon, in press b), and in the Bonnet Plume and Little Bear formations (Dixon, 1986).

The thin bedded nature of the bentonite and tuff beds, and the lack of current structures in the thicker beds, point to deposition from airborne ash falls, a conclusion also reached by Miall (1979). On Banks Island, the tuffs have an andesite-dacite composition and Miall (op. cit., p. 119) pointed out that their composition differs from that of the volcanic rocks in the northern Arctic Islands, leading him to conclude that they may have been derived from volcanoes in the Cordillera or west of Banks Island (presumably Canada Basin). Campanian-Santonian volcanic rocks are not known from the northern Canadian Cordillera; the acidic volcanic rocks of the Cordilleran Mount Nansen Group give radiometric ages within the Maastrichtian (Grond et al., 1984). It is possible that age-equivalent volcanic rocks in the northern Cordillera have not been identified, have been eroded, or that the bentonites and tuffs came from farther afield. Evidence of acidic volcanic activity in Canada Basin is lacking and, furthermore, this area is considered to be oceanic and a more basic type of igneous activity would be anticipated, if present.

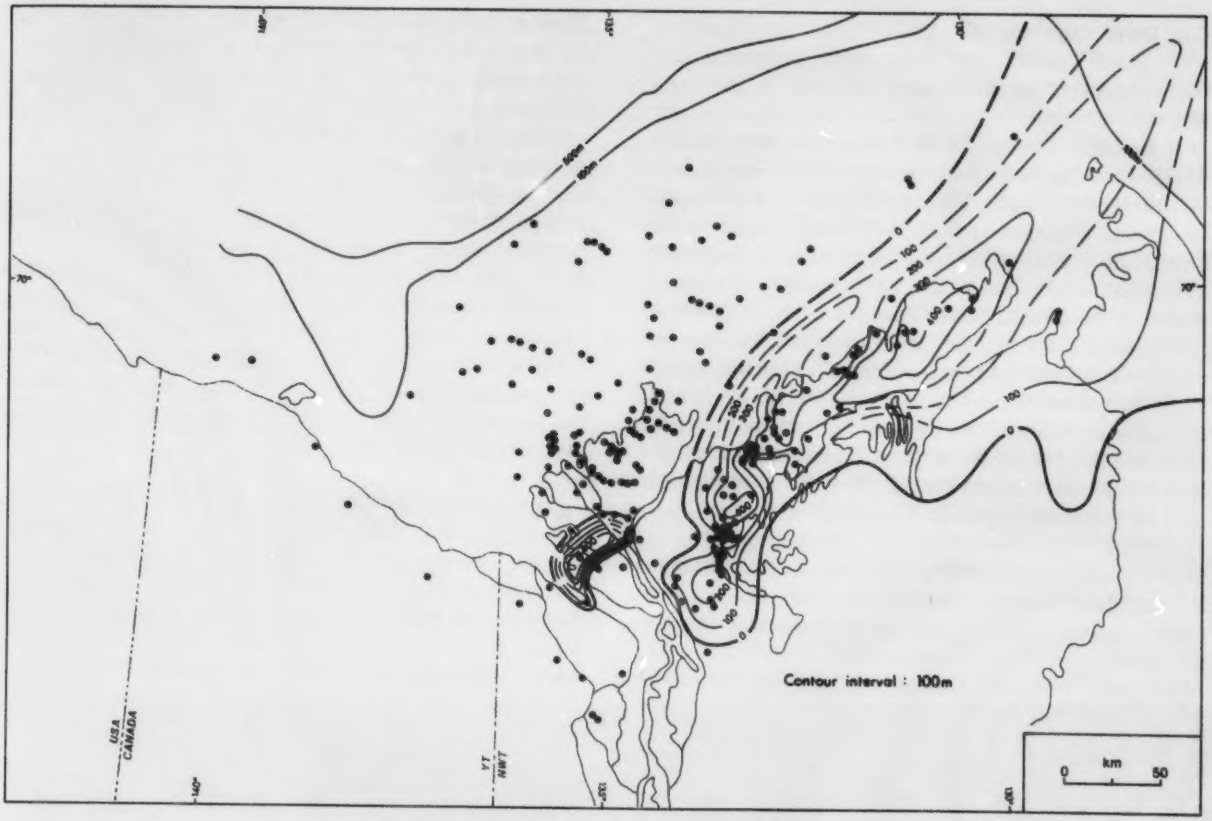

Figure 41. Isopach map, Smoking Hills Sequence.

Age and correlation

Smoking Hills strata on both the mainland and Banks Island contain few macrofossils and foraminifers. However, palynomorphs and dinoflagellates are abundant and constitute a very distinct Santonian–Campanian assemblage (Yorath et al., 1975; McIntyre, 1974). Yorath et al. (op. cit.) suggested that Smoking Hills strata were as old as Coniacian, but there is no definitive paleontological evidence to support this conclusion. McIntyre (op. cit.) identified two assemblage zones (H1 and H2) within the Smoking Hills outcrop strata and a third zone (H3) within the base of the overlying Mason River strata. Subsequent resampling of the type area (by McIntyre and Dixon in the summer of 1984) revealed inconsistencies with the original data, and all three floral zones were identified as occurring entirely within Smoking Hills strata.

On Banks Island, the age of the bituminous shale member of the Kanguk Formation was not specifically identified in Miall's (1979) regional work, although the oldest ages for the Kanguk Formation were given as Cenomanian. However, as previously pointed out (see section on Boundary Creek Sequence), this age is based on a questionable interpretation of foraminiferal information. Doerenkamp et al. (1976) identified a distinct floral assemblage (zone CV) in the bituminous shale member that is similar to the flora in the Smoking Hills Formation, thereby implying a Santonian–Campanian age. They also stated that there is no paleontological evidence to indicate the presence of Cenomanian to Coniacian strata (op. cit., p. 384).

Age-equivalent strata in the northern Yukon include the Burnthill Creek and Cody Creek formations (Dixon, in press b) of Eagle Plain, and part of the Bonnet Plume Formation, at the southern end of the Richardson Mountains. In the Norman Wells–Bear River area (N.W.T.) the Little Bear Formation is probably age equivalent. In Sverdrup Basin, equivalent strata are present in the Kanguk Formation (Embry, in press). In northern Alaska, some of the shales in the Colville Group (Molenaar, 1983) and the Hue Shale are correlative (Bird and Molenaar, 1987).

Fish River Sequence

Description and distribution

In northern Yukon, the Fish River Sequence consists of the Tent Island Formation and the sandstone beds of the Moose Channel Formation (i.e., it does not include the Ministicoog Member of the Moose Channel Formation). East of Mackenzie Delta, in Anderson Plain and under parts of Tuktoyaktuk Peninsula, shales of the Mason River Formation are included in the sequence. As a result of widespread erosion, no coarse clastic sediments are preserved in the upper part of the sequence in Anderson Plain. On Banks Island, the sequence includes the Kanguk Formation above the basal bituminous shale member. The upper sandstone member of the Kanguk Formation is the coarse clastic part of the sequence (Fig. 14).

Some of the correlations of Kanguk Formation on Banks Island suggested by Miall (1979, Fig. 8) have been revised. The log characters of and limited paleontological data from the Tiritchik M-48, Ikkariktok M-64, and Orksut I-44 wells are consistent with Miall's suggested correlations, but westward, in Uminmak H-07, Nanuk D-76 and Storkerson Bay A-15, alternative correlations are proposed (Fig. 19). The critical well for the reinterpretation is Uminmak H-07, where a Paleocene shale between log depths 449.9 and 640.1 m (1476-2100 ft.) was placed in the Kanguk Formation by Miall. It is herein suggested that this shale is equivalent to the shale member of the Eureka Sound Formation. Although the age of the Eureka Sound shale member is not well defined in the eastern wells, it would appear to be early Tertiary in age, based on the limited paleontological data from Ikkariktok M-64 and its relative stratigraphic position; both aspects strongly indicative of a Paleocene age. There are a number of physical attributes that point to alternative correlations. According to Miall, the equivalent strata of the shale member west of Orksut I-44 are sandy and coal bearing, which would impose an unusual lateral facies change on the generally westward progradation of Eureka Sound strata. If the Paleocene shale in Uminmak H-07 is acceptable as equivalent to the Eureka Sound shale member, then the upper part of the Kanguk Formation Miall identified in the Nanuk D-76 and Storkerson Bay A-15 wells also is of questionable correlation. In Uminmak H-07, between log depths 600 and 640.1 m (1968-2100 ft.), the resistivity logs have a distinctly ragged trace and the gamma-ray log tends to read slightly higher values of radioactivity than the adjacent strata — this latter feature is especially marked immediately above the subjacent beds. This log character can be traced into Nanuk D-76 and Storkerson Bay A-15 (Fig. 19), suggesting the physical continuity of the shale in these three wells. Although the paleontological data from D-76 and A-15 (Miall, 1979) indicate a Late Cretaceous age for the shale above the distinct resistivity zone, the accuracy of the data must be questioned when there is such a disparity between ages based on microfossils and palynomorphs, and where the intervals used in the biostratigraphic study are so broad. In Uminmak H-07, the paleontological data (Miall, 1979) are consistent between the two fossil groups (for a limited interval of strata) and the short intervals identified tend to favour a more accurate age determination. The distinct log character seen in the three western wells is not apparent in the Tiritchik M-48, Ikkariktok M-64, and Orksut I-44 wells.

If the revised correlations in the Banks Island wells are correct, then the Kanguk Formation is considerably thinner on west Banks Island than in the east. This could reflect the influence of the Storkerson Uplift on Kanguk deposition; it was possibly a relative high, although not necessarily a subaerial feature, during the Late Cretaceous, with the lower beds of the Kanguk onlapping (or downlapping) and eventually overlapping the high.

Throughout its known area of occurrence the Fish River Sequence has an abrupt or erosional lower contact. In the northern Yukon the basal beds contain a distinctive, coarse clastic unit (the Cuesta Creek Member) that unconformably overlies Boundary Creek strata. In Anderson Plain and under Tuktoyaktuk Peninsula, Fish River shales (Mason River Formation) rest abruptly on Smoking Hills shale. There is no apparent scour at the contact between the Mason River and Smoking Hills shales when viewed at individual locations, but, on a regional scale, there appears to be some very low-angle truncation of Smoking Hills strata (Fig. 40). On Banks Island, the contact between the bituminous and silty shale members of the Kanguk Formation was not described by Miall (1979), but his illustration (op. cit., Plate 10, p. 36) suggests an abrupt contact.

The upper contact of the Fish River Sequence also is abrupt or erosional. In the northern Yukon, shale of the Ministicoog Member (Aklak Sequence) overlies Fish River sandstones. A similar situation exists on Banks Island, where the shale member of the Eureka Sound Formation rests abruptly on sandstone of the Kanguk Formation (Fish River Sequence). At the southern end of Caribou Hills and in the Kipnik O-20 and Ogruknang M-31 wells, Fish River strata have been eroded. This erosional feature has been called the Caribou High by Young et al. (1976, Fig. 3).

The lower part of the Fish River Sequence is shale-dominant but a local coarse clastic unit (Cuesta Creek Member) is present in the northern Yukon. Strata of the Cuesta Creek Member consist of interbedded conglomerate, sandstone and shale. Holmes and Oliver (1973), Young (1975), and Dixon (1988) have described in detail the lithofacies and they will not be repeated here. In general terms the strata tend to be thin to medium bedded; beds generally are tabular, although groups of beds can occupy large scours (Fig. 42). Sedimentary structures mostly consist of fine, subhorizontal, and ripple laminae in the sandstones. Many beds are massive in appearance. A variety of sole marks are locally present, especially on sandstone and siltstone beds. Cuesta Creek beds are present in outcrops throughout the northern Yukon and can be traced into nearby wells (e.g., Fish River B-60, Fig. 21), but there is a tendency for the basal coarse clastics to become thinner, siltier and shalier in a basinward direction. Under Tuktoyaktuk Peninsula, in Anderson Plain and on Banks Island, there are no prominent basal coarse clastic sediments.

Overlying the Cuesta Creek beds is a thick succession of shale with thin (mm- to cm-thick) interbeds of very fine grained sandstone and siltstone. The shales are light to medium grey and generally soft. Pebbly and convoluted shales locally overlie Cuesta Creek beds (Young, 1975). In Anderson Plain and Banks Island, Fish River shales are light grey and very soft (Fig. 39), and contain concretion-rich and ferruginous shale intervals in the middle part of the succession. The concretionary and ferruginous shale intervals weather a rusty brown and impart a banded appearance to the rocks. Coarse clastic material is limited to very thin beds of sandstone and siltstone in the shale-dominant succession of northern Yukon and Anderson Plain, but on Banks Island there is a prominent sandstone interval within the Kanguk shale, which Miall (1979) identified as the lower sand member. The lower sand member consists of a coarsening-upward succession, with interbedded and interlaminated, very fine to fine grained sandstone and shale at the base grading up into coarse grained to pebbly sandstone at the top.

Figure 42. Cuesta Creek strata (basal Fish River Sequence) along Fish River. Note the large-scale scour (arrows) and the low-angle foresets in strata below. View to the northeast. ISPG photo. 2846-23.

In the western Beaufort Sea and northern Yukon the Fish River shales are overlain by a thick succession of deltaic rocks consisting of interbedded conglomerate, sandstone, shale, and, locally, coal. In Anderson Plain and under Tuktoyaktuk Peninsula the upper beds have been eroded, and on Banks Island only a thin sandstone interval is present (upper sandstone member of the Kanguk Formation, Miall, 1979). This unit appears to shale out laterally between the Uminmak H-07 and Nanuk D-76 wells (Fig. 19).

Based on the stratigraphic interpretation of reflection seismic data it is believed that the Fish River Sequence is thickest in the west Beaufort Sea, where it may be up to 6000 m thick (Fig. 43). Only on the basin margins are complete thicknesses known; for example, in the Fish River B-60 well there are 1701 m of strata and in Reindeer D-27, 360.9 m. This general easterly thinning appears to be a depositional trend and is readily seen in the thinning of the deltaic facies within the sequence. In Anderson Plain the Fish River Sequence (Mason River Formation) is less than 200 m thick. On Banks Island the thickest known section is in Orksut I-44, where there are approximately 370 m of Fish River strata. Offshore Banks Island the Fish River Sequence is less than 200 m thick (Fig. 43), but probably thickens basinward of the Arctic Platform Hinge Line.

Depositional environments

Fish River strata represent a complete range of depositional facies, from deep water sediment, gravity flow deposits, through slope and shelf shales into delta front and delta plain sandstones and shales (Fig. 44). All of these sediment types are present in the outcrop belt of the northern Yukon. Submarine fan and channel deposits are represented by the Cuesta Creek beds (Fig. 42; Dixon, 1988). Immediately overlying the

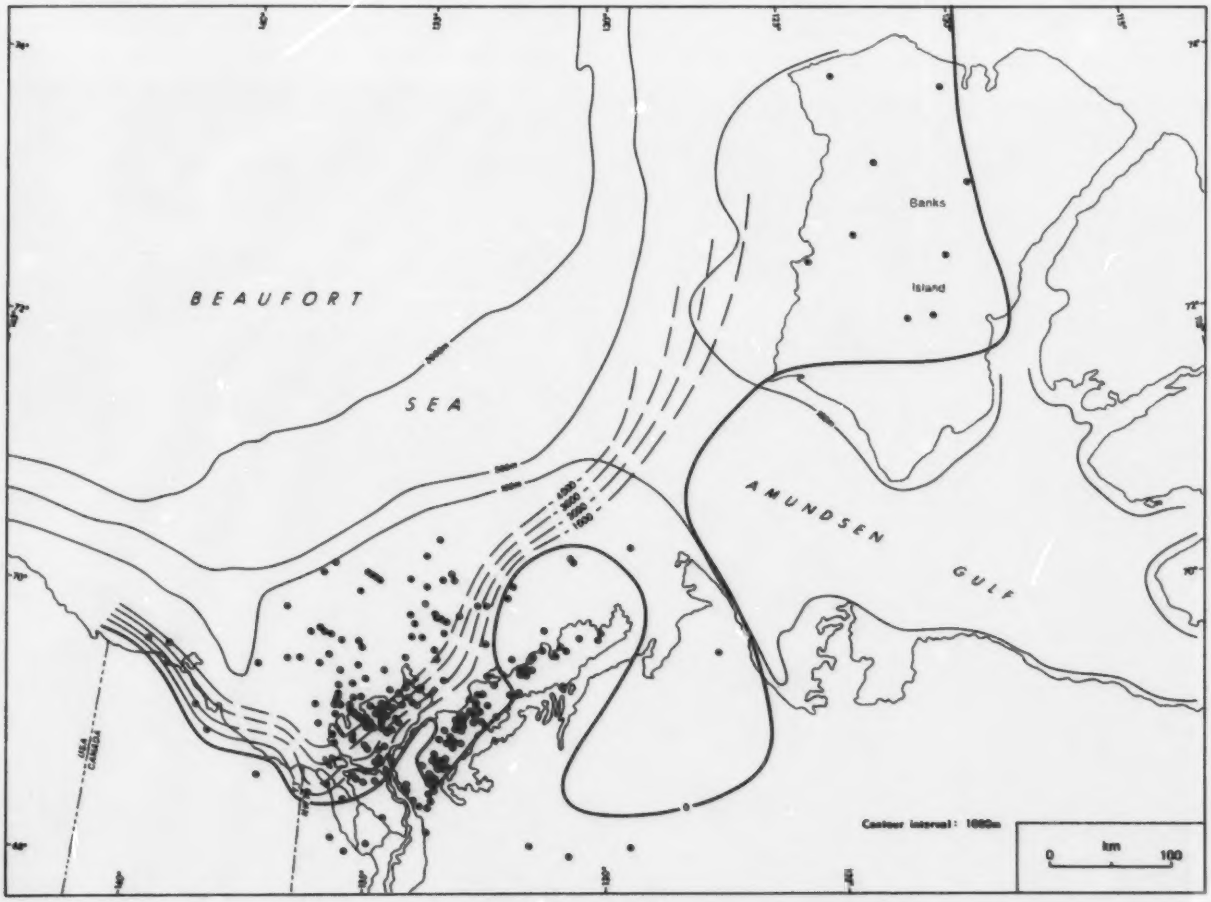

Figure 43. Isopach map, Fish River Sequence.

Cuesta Creek beds is a thick shale succession (Tent Island Formation) that is interpreted as a slope and shelf deposit. The shales are succeeded by a thick interval of interbedded sandstone and shale (sandstone member of the Moose Channel Formation), of deltaic origin.

The main locus of deltaic deposition was in the Herschel Island–Mackenzie Bay area (Fig. 44), a conclusion based upon the interpretation of delta plain facies in the Natsek E-56 well (using log signature, lithological succession, and the presence of thick coal seams), and correlation of the reflection character through this well to similar facies types seen on reflection seismic data from the Mackenzie Bay area. Interpretation of reflection seismic data in the Natsek area indicates that up to 2500 m of reflective deltaic strata overlie 2000 m of nonreflective, presumably shale-dominant, shelf and upper slope deposits of the Fish River Sequence. The maximum basinward extent of the Fish River delta has not been documented with any degree of certainty, because of a lack of well control and uncertain seismic facies interpretation in areas where the sequence is highly folded. However, based on the size of younger deltas (e.g., Kugmallit delta and the modern delta), which could be used as analogues, the Fish River delta may have extended an additional 30 to 50 km north of Natsek E-56.

The known lateral extent of deltaic facies (based on well data) is from Natsek E-56 to Mackenzie Delta, a distance of about 200 km. Deltaic strata in the D-27 well are relatively thin and probably are near the eastern limit of deltaic deposition. Most of the Fish River Sequence in the Mackenzie Delta area is characterized seismically by low amplitude, discontinuous reflections, interpreted as denoting shale-dominant shelf and possibly slope deposits (Figs. 4, 5). The westward limit of deltaic strata is not known, although the seismic character of intervals interpreted

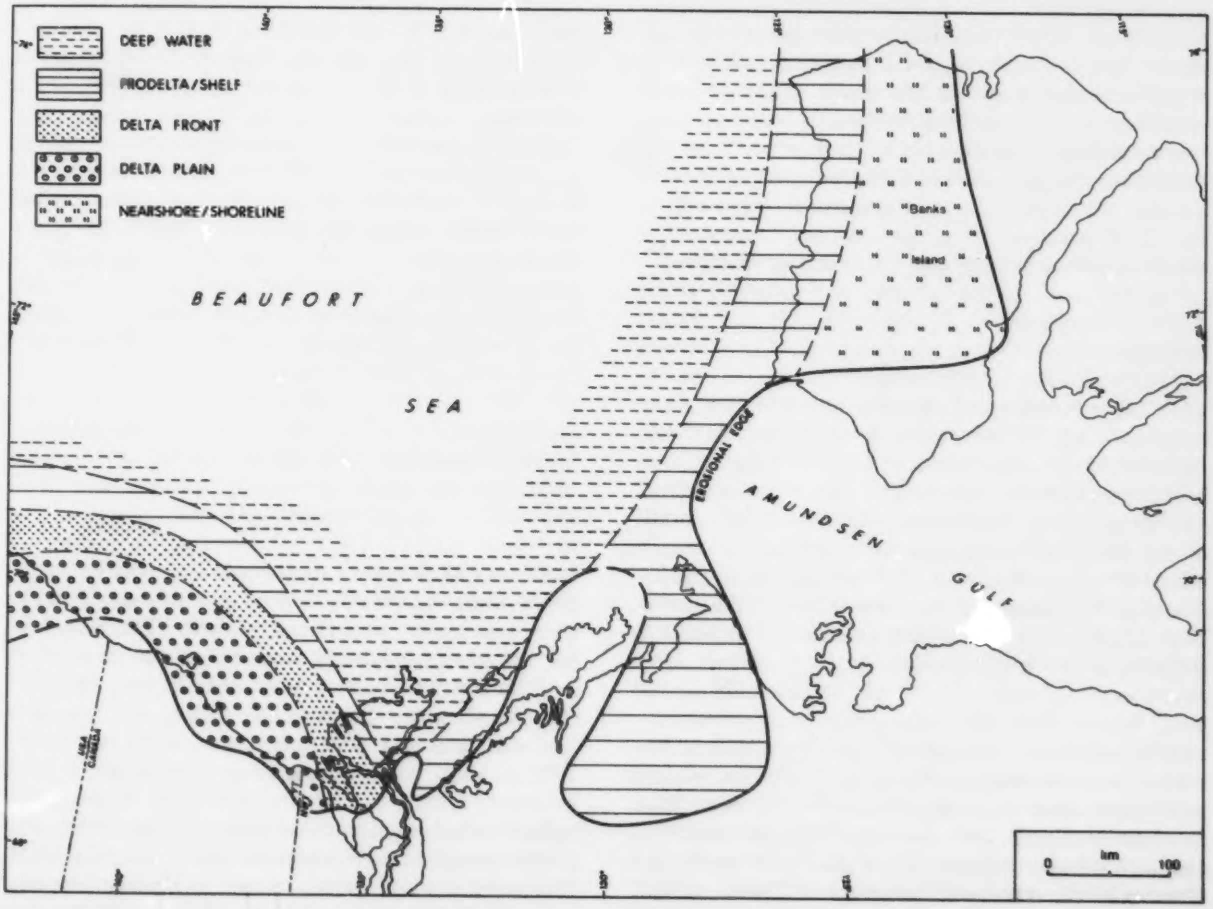

Figure 44. Interpreted Fish River Sequence depositional environments at time of maximum progradation.

as Fish River Sequence suggest that deltaic strata extend into the Alaskan part of the Beaufort Sea. Beneath the eastern Beaufort shelf, in the vicinity of the Kilannak well, outer shelf, slope, and deep water deposits of the Fish River Sequence have been identified from seismic data (southeastern end of reflection line in Fig. 7).

In Anderson Plain and under parts of Tuktoyaktuk Peninsula, shelf, and possibly some slope shales are present. Whether coarser clastics were ever deposited in this area cannot be determined, as a result of erosion of the upper part of the Fish River Sequence. The known location of the main deltaic succession and comparison with Banks Island suggest that there was a minimal supply of coarser clastic material to Anderson Plain during deposition of the Fish River Sequence.

Banks Island contains a relatively thin Fish River Sequence, dominated by shelf shales of the Kanguk Formation. The two sand bodies within the Fish River Sequence of Banks Island are relatively thin and pass westward into shelf shale. Miall (1979) interpreted both sand bodies as sand bars, with shoreface and foreshore facies, deposited over localized shoals. Only the upper sandstone member has been mapped at the surface; the lower sandstone appears to be present only in the subsurface. Using the depositional sequence concept as a guide, the upper sandstone member is interpreted as the final product of progradation, representing deposition on a prograding, basin-margin shoreline.

Age and correlation

In early descriptions of strata from the Fish River Sequence of the mainland, the oldest age was considered to be Santonian or Campanian for the Tent Island Formation (Young, 1975) and Campanian for the Mason River Formation (McIntyre, 1974; Yorath et al., 1975). A Campanian age for strata on Banks Island also was suggested (Doerenkamp et al., 1976; Miall, 1979). Subsequent work by Sweet (1978) limited Tent Island strata to the Maastrichtian, and possibly only the late Maastrichtian. McIntyre's (op. cit.) microfloral divisions, H1 to H3, included H3 in the basal Mason River Formation. However, subsequent resampling revealed that the H3 division occurs in the underlying Smoking Hills strata. The overlying microflora have more Maastrichtian affinities than Campanian (Sweet, pers. comm., 1985); consequently, the age of the Mason River shale is probably Maastrichtian, consistent with what is known for the Tent Island Formation, although a late Campanian age cannot be totally ruled out. Doerenkamp et al. (op. cit.) identified a similar microfloral zone (zone CVI) in the Kanguk Formation above the basal bituminous member on Banks Island and concluded that it was mostly Maastrichtian, although a late Campanian age for the lowermost strata was considered possible.

The youngest age for Fish River strata is considered to be Early Paleocene, based on the presence of foraminifers of the *Verneuillioides* sp. 3495 Interval Zone (McNeil, 1989) in the sandstone-dominant (Moose Channel Formation) part of the sequence. Because the deltaic strata are encased between upper Maastrichtian and Paleocene beds it is possible that they are Early Paleocene in age.

Coeval strata in northern Canada include the East Fork and Summit Creek formations in the Norman Wells area (Yorath and Cook, 1981), and possibly part of the Bonnet Plume Formation at the southern end of the Richardson Mountains (Dixon, 1986). In northeastern Alaska, the upper part of the Colville Group and possibly the lower beds of the Sagavanirtok Formation are coeval (Molenaar, 1983), as well as the Canning Formation (Bird and Molenaar, 1987). The Kanguk Formation occurs throughout the Sverdrup Basin, although its lowermost beds appear to be older in the more basinward occurrences than at the exposed basin margins (Embry, in press). On Axel Heiberg and Ellesmere islands, the Expedition Fiord Formation of the Eureka Sound Group appears to be correlative with the Fish River Sequence (Ricketts, 1986), as is the upper part of the Kanguk Formation on Bylot Island (Miall et al., 1980).

Aklak Sequence

Description and distribution

The Aklak Sequence, first named by Dietrich et al. (1989), is equivalent to the lower part of the previously named Reindeer Sequence (Fig. 12). The Reindeer Sequence was originally defined as the succession extending from the base of the Ministicoog Member (Moose Channel Formation) to the base of the Richards Sequence (Dietrich et al., 1985), a 4000 to 5000 m thick succession with its depocentre in the Richards Island–Mackenzie Bay area. Subsequent analysis of seismic and biostratigraphic data led to the identification of two sequences within the Reindeer succession, which Dixon et al. (1985) informally designated the Lower and Upper Reindeer sequences.

The Natsek E-56 well (Fig. 22B) provided the first evidence for a twofold division of the Reindeer Sequence. There, a prominent seismic sequence boundary (feature number 4 on Figure 4) separates two very distinct seismic facies: high amplitude, near continous reflections below; and low amplitude, discontinuous reflections above. Also, there is an abrupt lithological change across the unconformity, from interbedded sandstone, conglomerate, shale and coal below, to shale and silty shale above. This unconformity was originally interpreted as the Reindeer/Fish River contact by Dietrich et al. (1985), but more recent biostratigraphic studies have shown it to be an intra-Reindeer unconformity (Dietrich et al., 1989). This major angular unconformity, which is imaged on seismic profiles in several parts of the western Beaufort–Mackenzie Basin (Figs. 4, 9), divides the Reindeer succession into two sequences, the Aklak and Taglu. The names are derived from the Aklak Member of the Reindeer Formation (Young, 1975) and the informally named Taglu member or beds of the Reindeer Formation (Shawa, 1979). In the Mackenzie Delta area, the Aklak–Taglu unconformity is not clearly imaged on seismic profiles (Fig. 29), although biostratigraphic data from several wells allow for local differentiation of Aklak and Taglu strata. The realization that the original Reindeer Sequence, and also the formation, contain two major depositional sequences changes some of the earlier correlations of Young et al. (1976) and Young and McNeil (1984). These authors identified Moose Channel strata (i.e., Fish River Sequence) now placed in the Aklak Sequence, in some of the Mackenzie Delta wells. But in a lithostratigraphic context these strata are still part of the Reindeer Formation (sensu Price et al., 1980; i.e., strata between the Ministicoog Member and the Richards Formation). These earlier correlations were based on the presence of a distinct shale unit, within a sandstone-dominant succession, which was identified as the Ministicoog Member of the Moose Channel Formation in the Ellice O-14 well ("Ellice Shale" in Fig. 21). This shale interval we consider to be the basal beds of the Taglu Sequence. The reinterpretation is supported by the presence of the *Portatrochammina* assemblage within this shale interval, which is distinct from the foraminifers found in the older Ministicoog shale (McNeil, 1985). Wells on the outer part of the Mackenzie Delta that penetrated Reindeer strata rarely extend below the Taglu Sequence.

In the Beaufort–Mackenzie Basin, the Aklak Sequence consists of the Ministicoog Member of the Moose Channel Formation, the Aklak Member of the Reindeer Formation, and all laterally equivalent facies. All of the outcrops of these strata in the northern Yukon and at Caribou Hills can be assigned to the Aklak Sequence. On Banks Island, it would appear that all of the Eureka Sound Formation is included in the Aklak Sequence. The Paleocene shale member of the Eureka Sound Formation (Miall, 1979) is the right age and in the same relative stratigraphic position to be correlative with the Ministicoog shale. At Caribou Hills, the lowermost beds of the sandstone succession contain a Ministicoog-type fauna (Price et al., 1980) and, although the lithology is similar to the overlying Reindeer Formation, Price et al. (op. cit.) identified the lowermost 60 m as Moose Channel Formation. At Caribou Hills the sandstone succession rests on much older Smoking Hills strata. The Caribou Hills section is important in understanding the reason for including the Ministicoog in the Aklak sequence; it is here that physical and paleontological evidence indicates a major erosional unconformity below strata correlative with the Ministicoog shale on Fish River, where the Ministicoog shale is conformable on Moose Channel sandstones. The erosional unconformity at the base of the Aklak Sequence is readily seen in reflection seismic data in the Caribou Hills area (Fig. 38), and can be traced through the wells at the southern end of Tuktoyaktuk Peninsula (Fig. 23). It is obvious from this brief description that the Fish River/Aklak contact is erosional to disconformable along the central and southeastern basin margin.

In the west Beaufort, the lower boundary of the Aklak Sequence has been tentatively identified in the Natsek area where it appears seismically as a subtle truncation and onlap surface within a deltaic succession (Fig. 4). Elsewhere in the western part of the basin, the Fish River/Aklak boundary has not been identified with any certainty. On Banks Island the lower contact of the Aklak Sequence is conformable. In the Caribou Hills, Oligocene strata of the white-clay unit (Price et al., 1980), considered to be part of the Kugmallit Sequence, erosionally overlie the Aklak Sequence. On Banks Island, the Miocene Beaufort Formation rests erosionally on Eureka Sound strata. Offshore from Banks Island, the Plio–Pleistocene Iperk Sequence may rest abruptly on Aklak (Eureka Sound) strata.

The lithology of the penetrated and exposed Aklak Sequence in the Beaufort–Mackenzie Basin is mostly interbedded sandstone, siltstone and shale with some areas containing abundant coal beds (e.g., Natsek E-56 and in outcrop along Aklak Creek, northern Yukon). Northeast of the Parsons Lake area (Tuktoyaktuk Peninsula) the Aklak Sequence becomes progressively siltier and shalier in its lower part (Fig. 23); eventually only the uppermost beds contain sandstone. The Ministicoog shale is a prominent local facies present in the outcrop belt of the northern Yukon and the immediately adjacent wells. Both coarsening-upward and fining-upward units are present in the Aklak Sequence. Shale interbeds become thicker and coarsening-upward units more common in the more basinward wells of the Mackenzie Delta. No wells have penetrated basinal facies of the Aklak Sequence, although some seismic profiles image shelf-to-slope transitions (clinoforms) in local areas (e.g., Figs. 7, 29, 31). Similar facies are present in equivalent strata on Banks Island (Miall, 1979), but the Aklak Sequence has not been drilled in the offshore areas. Seismic reflection data show that the lower Aklak Sequence contains shelf edge clinoforms, approximately 50 to 60 km from Banks Island (Fig. 8), overlain by topset reflections of probable shelf deposits. From the western shoreline of Banks Island to the paleoshelf margins, the sequence may change from sandstone-dominant deltaic deposits to shale-dominant shelf deposits, but there are no consistent seismic reflection character changes to indicate where this transition occurs.

At the southern margin of the Beaufort–Mackenzie Basin, incomplete sections of Aklak strata are about 750 m thick at Caribou Hills and 500 m at Fish River B-60. Strata thicken rapidly basinward and the sequence is up to 2000 m thick north of the Natsek well. Thicker sections of Aklak strata (+4000 m) occur in the western Beaufort Sea area (Fig. 45). A few complete sections of Aklak strata have been penetrated; for example, 695 m at Natsek E-56 and 204 m at Reindeer D-27.

In the Banks–Beaufort Basin, only incomplete successions of the Aklak Sequence are known and these range in thickness up to 1000 m. Offshore, seismically identified Aklak strata are generally no more than 3000 m thick (Fig. 45).

Depositional environments

The known strata of the Aklak Sequence contain prodelta/shelf sediments (e.g., Ministicoog shale and the Paleocene shale member on Banks Island) and delta front to delta plain facies. In the Beaufort–Mackenzie Basin, the deltaic sediments have an east-west extent from Natsek E-56 to the Wagnark area on Tuktoyaktuk Peninsula, a distance of about 250 km (Fig. 46). The basinward extent of the deltaic facies is largely unknown, although the Natiak O-44 well penetrated probable shelf equivalents. Using the Natiak well as a control point, and by analogy with the Kugmallit and modern deltas, deltaic strata may have extended at least another 30 km basinward, and perhaps up to 50 km, from the Natsek well. There is a concentration of thick coal seams in the western and central parts of the deltaic facies — in the outcrops at Aklak Creek and especially in the Natsek E-56 well. Deltaic sediments begin to shale out in a northeasterly direction, along the length of the Tuktoyaktuk Peninsula. Deltaic strata within the Aklak and underlying Fish River sequences probably occur in substantial thickness in the Kaktovik Basin, offshore Alaska.

Deltaic strata underlie much of Banks Island (Fig. 46; Miall, 1979) and are known as far west as the Storkerson Bay A-15 well, very close to the western coast. Consequently, similar strata must extend into offshore areas, but to an unknown distance. Onshore, the wells contain typical coarsening-upward, delta front to delta plain units, and fining-upward, delta plain fluvial units (Miall, 1979).

Aklak and Fish River deltaic strata in the Banks–Beaufort and Beaufort–Mackenzie basins are rich in coal, containing much more than any of the other Tertiary deltaic successions. Although poor preservation of similar facies in younger sequences could be a possible reason for lack of coal in the Miocene sequences, this is not the case for the Kugmallit and Iperk sequences, in which large tracts of coal-poor, delta plain deposits are preserved. The abundance of coal in Paleocene and Eocene strata may be a result of climate, rates of sedimentation and basin subsidence, and/or changes in the types of vegetation. The Paleocene and Eocene were times of warm, temperate climates in the Arctic areas, in contrast to the cooler climatic conditions that were prevalent in Oligocene and later times (McNeil, 1989).

Areally large and thick accumulations of Aklak strata are present in the two basins, in contrast to the previous deltaic deposits of the Fish River Sequence, where only the Beaufort–Mackenzie Basin had a significant delta accumulation. The two delta complexes had differing source areas: the Beaufort–Mackenzie delta complex had a southerly provenance, and the Banks–Beaufort delta complex received its sediments from the east and southeast (Miall, 1979). Although the two delta complexes had a large areal extent at their maximum progradation, it is unlikely that the two complexes overlapped at their margins, as is evident from the almost complete lateral shale-out of deltaic strata in the vicinity of the Tuk wells on

Tuktoyaktuk Peninsula. In the area off northern Tuktoyaktuk Peninsula, only shale-dominant shelf and slope deposits of the Aklak succession have been identified. In neither case can it be demonstrated that the two delta complexes were fed by single trunk rivers or that they represent an amalgamation of several smaller coastal deltas.

Age and correlation

Aklak strata contain foraminifers of the *Reticulophragmium* Assemblage Zone and from the lower part of the *Portatrochammina* Assemblage Zone (McNeil, 1989). McNeil (op, cit.) also identified two Interval Zones within Aklak strata, the *Reticulophragmium borealis* and *Portatrochammina* sp. 2849 zones. The foraminifers indicate a Late Paleocene to Early Eocene age for Aklak strata. Pollens and spores are not very abundant and are similar to those present in underlying Paleocene strata. The upper beds of the Aklak Sequence locally contain foraminifers of the *Portatrochammina* assemblage, the age of which is not well documented. Based on its occurrence between known Paleocene and Eocene assemblages, McNeil (1985) concluded it was Late Paleocene or Early Eocene in age. On Banks Island, strata equivalent to the Ministicoog shale have been dated as Paleocene but the overlying deltaic beds have not been well dated, although ages as young as Eocene are indicated (Miall, 1979).

In northern Alaska, part of the Sagavanirktok Formation is correlative with the Aklak Sequence (Bird and Molenaar, 1987). Very little is known about Late Paleocene strata south of the Beaufort-Mackenzie Basin, although some strata of the Bonnet Plume Formation at the southern end of the Richardson Mountains may be as young as Late Paleocene (A.R. Sweet, pers. comm., 1986). Equivalent strata are

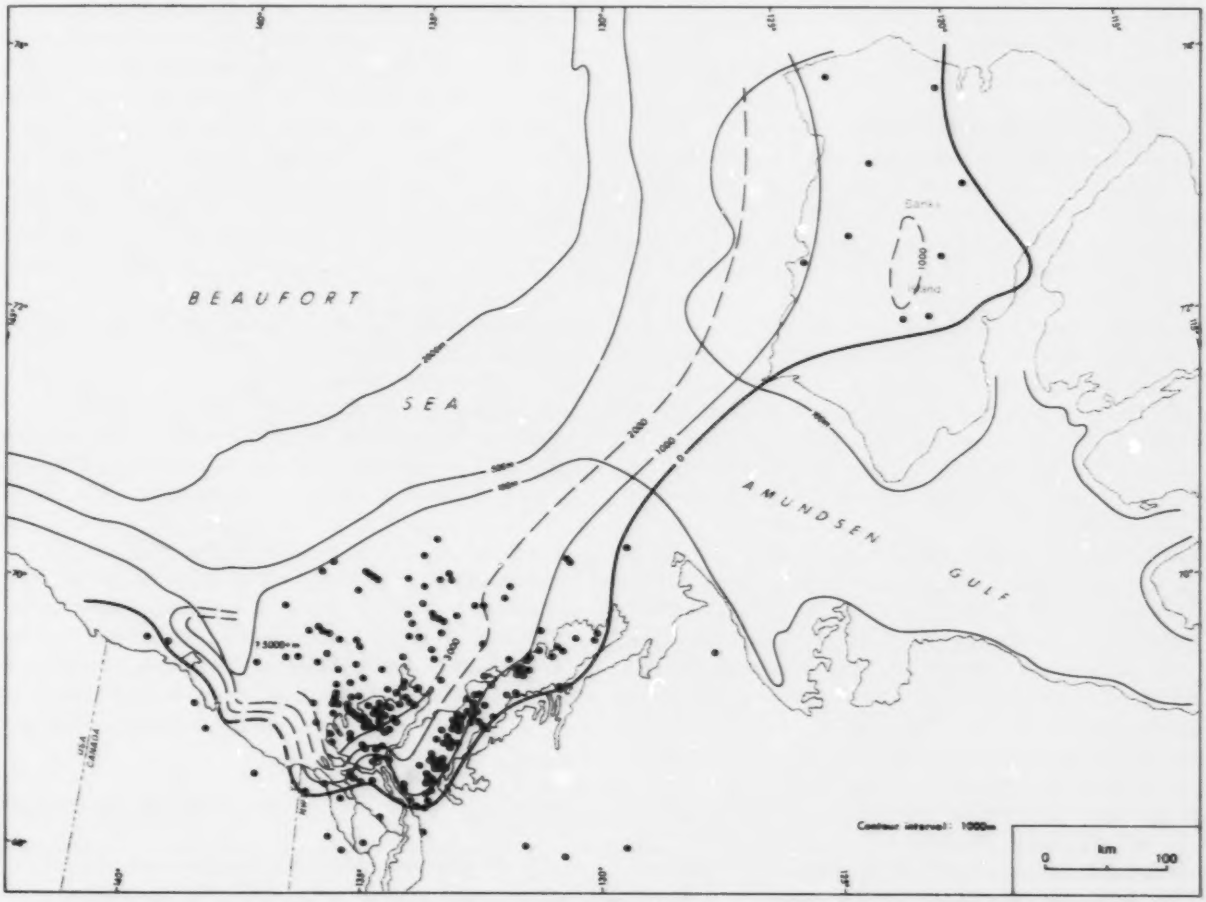

Figure 45. Isopach map, Aklak Sequence.

present in the Eureka Sound Group (sensu Ricketts, 1986) of the Arctic Islands, specifically the Strand Bay Formation, and part, or all, of the Iceberg Bay Formation (Wall et al., 1988).

Taglu Sequence

Description and distribution

The Taglu Sequence was first named by Dietrich et al. (1989). It is the upper part of the previously identified Reindeer Sequence (Dietrich et al. 1985). As previously noted, the Aklak/Taglu sequence boundary was initially identified in the Natsek well in the western part of the basin. There, shale-dominant shelf and slope deposits of the Taglu Sequence unconformably overlie deltaic strata of the Aklak Sequence (Fig. 4). In the Mackenzie Delta area, the Aklak/Taglu contact is not clearly imaged on seismic profiles and can only be identified in some wells, principally using biostratigraphic data. In the Reindeer D-27 well, the sequence boundary is interpreted as occurring at a log depth of 2712.7 m, at the base of a thick deltaic and shelf succession that contains foraminifers of the *Portatrochamina* Assemblage Zone (an assemblage zone typical of Taglu strata). In the Ellice O-14 well (Fig. 21) the Aklak/Taglu contact occurs within a deltaic succession. In the Ellice well, the sequence boundary is chosen at the base of a shale section (1830 to 2027 m log depths) that underlies large-scale, coarsening-upward, delta front deposits of the Taglu Sequence. Young (1975) and Young et al. (1976) originally identified this shale as the Ministicoog Member, Moose Channel Formation, but biostratigraphic data indicate that the shale interval is younger than the Ministicoog and correlates more closely with the lower Taglu Sequence in the Natsek area (McNeil,

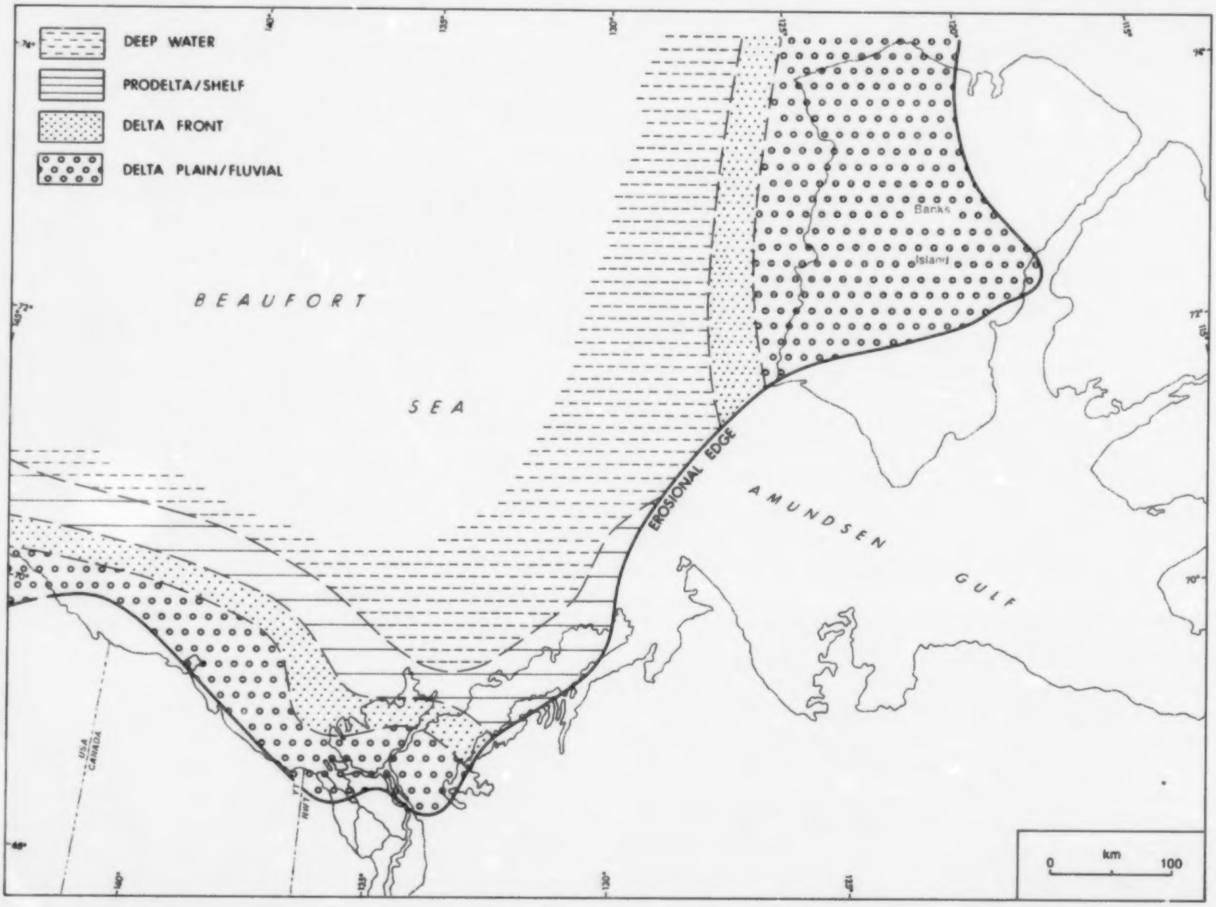

Figure 46. Interpreted Aklak Sequence depositional environments at time of maximum progradation.

1989, Fig. 4). The shale section seen in Ellice O-14 can be correlated with North Ellice J-23 and Langley E-29, but farther north the correlation becomes less certain (Fig. 21).

The upper boundary of the Taglu Sequence is readily recognized on reflection seismic profiles in many parts of the basin (Figs. 5, 6, 9, 29), but only under Mackenzie Delta is there a marked lithological contrast. Under Mackenzie Delta, the Taglu Sequence comprises interbedded sandstone, shale and some coal, whereas the overlying Richards Sequence consists mostly of shale. The upper boundary of the Taglu Sequence in the Mackenzie Delta area provides an insight into the relationships between formational boundaries, hiatal (maximum flooding) surfaces, and unconformities in a conformable basinal position. The Reindeer Formation (sensu Price et al., 1980, and Young and McNeil, 1984) is placed at the top of the uppermost sandstone. An unconformity or disconformity is interpreted as occurring at some depth (a few metres to tens of metres) below the lithological (formational) boundary. However, the location of the unconformity or disconformity cannot be objectively identified from wireline or lithological logs of the succession; consequently, the maximum flooding surface is used to define our sequence boundary in this type of basinal setting (Fig. 47, in pocket; Dixon and Dietrich, 1988). The low-velocity shale commonly present above the flooding surface represents a condensed section.

Taglu strata are known from the west Beaufort, under Mackenzie Delta, and parts of the central Tuktoyaktuk Peninsula. The most northerly known occurrence is in the Tarsiut area. Northeast of Tuktoyaktuk Peninsula, Taglu strata appear to have been totally eroded, at least at the basin margins. No Taglu strata are known in the Banks–Beaufort Basin.

The thickest accumulation of Taglu strata is believed to be under the outer reaches of Mackenzie Delta, where there are probably 2500 to 3000 m of sediment (Fig. 48). Toward the basin margins the sub-Iperk unconformity cuts directly into Taglu strata. No known exposures of Taglu rocks are present in the Beaufort–Mackenzie Basin.

Depositional environments

Three known depositional facies assemblages have been drilled in the Taglu Sequence: deep water, prodelta/shelf, and deltaic sediments. Deep water and prodelta/shelf sediments are predominantly shale and are present in the western part of the basin (Fig. 49). Inclined reflections in the Natsek area (Fig. 4), which appear to be shelf clinoforms, indicate that a shelf edge prograded in a northwesterly direction in this part of the basin. These clinoforms can be traced into the Edlok area where Taglu strata contain a sandstone-rich interval interpreted as submarine fan or slope apron deposits (Dietrich et al., 1989). Deltaic sediments are present under the eastern parts of Mackenzie Bay, Mackenzie Delta and the southern Tuktoyaktuk Peninsula (Fig. 49). Within the delta deposits, fluvial-dominant sediments are present to the south; for example, in the Ellice O-14 area. Delta front deposits become more abundant to the north of the Ellice area. Depositional facies to the north and northeast of the deltaic rocks are poorly known, principally because of a lack of well penetrations, the most northerly penetration being at Amerk O-09. Shelf to deep water sediments are interpreted as lying in a basinward direction from the main delta depocentre.

Age and correlation

The lower beds of the Taglu Sequence contain foraminifers of the *Portatrochammina* Assemblage Zone and the *Portatrochammina* sp. 2000 Interval Zone (McNeil, 1989). The known upper beds of the sequence are generally barren of foraminifers. The age of Taglu strata, indicated by palynomorphs and foraminifers, is Early to Middle Eocene. Palynomorphs are present throughout the Taglu Sequence (McIntyre, 1985). An Early Eocene flora has been found locally (e.g., at Natsek E-56, Dietrich et al., 1989) within Taglu strata but the bulk of the palynomorphs from the upper part of the sequence extend into the overlying Richards Sequence. These are either Early or Middle Eocene in age.

Eocene strata in northern Canada, outside of the Beaufort–Mackenzie Basin, are not well documented. Ricketts (1986) indicated that part of the Iceberg Bay Formation (Eureka Sound Group) on Axel Heiberg and Ellesmere islands extended into the Eocene, and could be age-equivalent to the Taglu Sequence. Miall (1986) indicated that parts of the Eureka Sound Group throughout the Arctic Islands are Eocene in age (Miall uses a different formational terminology from Ricketts). Seismic correlations suggest that Taglu strata may occur locally in the Alaskan Beaufort Sea. In northern Alaska, part of the Sagavanirktok Formation probably contains age-equivalent strata (Bird and Molenaar, 1987).

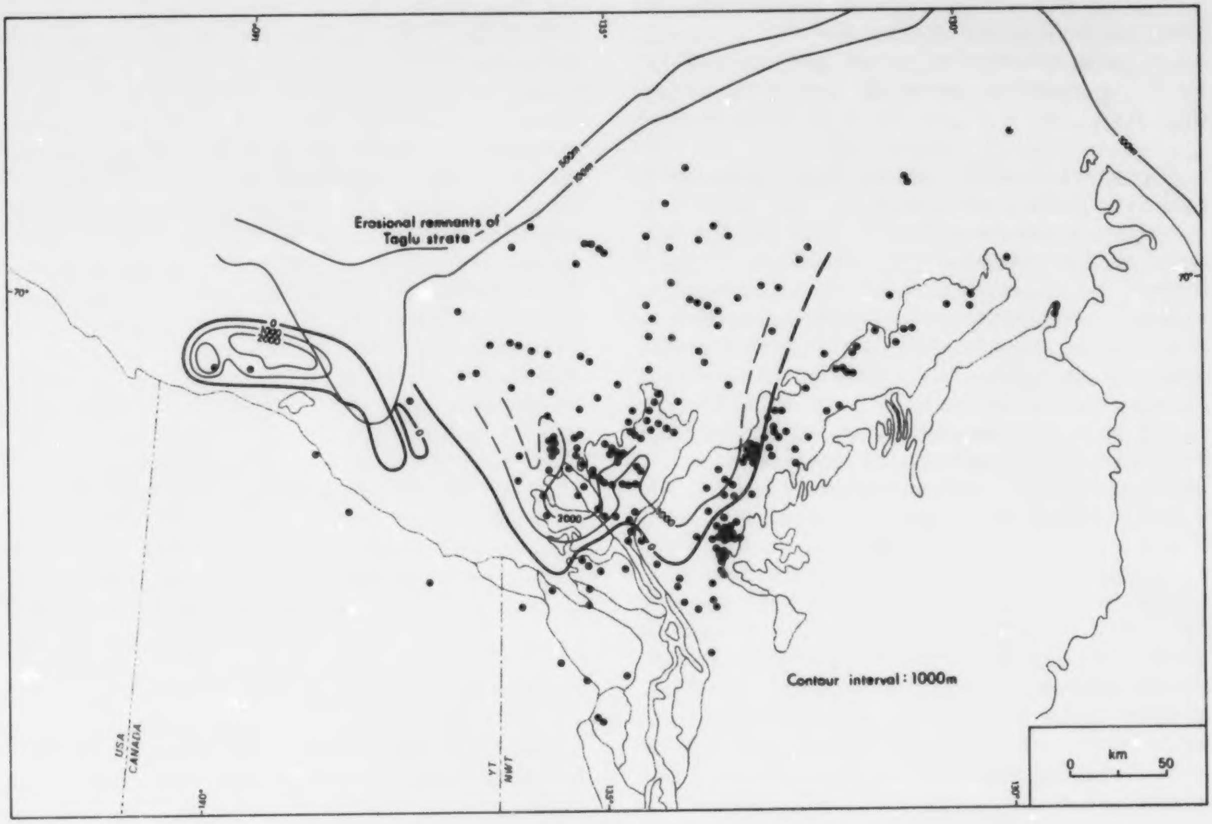

Figure 48. Isopach map, Taglu Sequence.

Richards Sequence

Description and distribution

Strata of the Richards Sequence are present only in the Beaufort-Mackenzie Basin and are partly equivalent to the Richards Formation (Young and McNeil, 1984). The lower boundary is an abrupt, conformable contact throughout most of the basin but in places it is a significant erosional unconformity (Figs. 4, 9, 29). Under most of Mackenzie Delta, beds immediately overlying the sequence boundary are low-velocity shales. They are of variable thickness and the interval is readily identified on sonic logs (Fig. 47). The seismic signature of the low-velocity shales is also prominent, consisting of either a generally reflection-free interval or one in which there are only weak, discontinuous reflections (Figs. 5, 29).

The nature of the upper boundary of the Richards Sequence varies according to basin position. Under the outer Beaufort shelf, significant shelf margin erosion of Richards strata can be seen on some reflection seismic profiles (Fig. 18). When traced southward the obvious erosion becomes less pronounced and an apparent conformable contact between Richards and overlying strata is seen on reflection profiles (Figs. 4, 9).

In the Alerk area a major submarine canyon has cut into Richards strata (Fig. 31). This erosional surface is overlain by Kugmallit strata. Seismic correlations of the erosional sub-Kugmallit unconformity from the Alerk P-23 to the Kugmallit H-59 wells indicate that the Richards/Kugmallit sequence boundary occurs in a continuous deltaic succession in the H-59 well (log depth 1759 m).

The Richards/Kugmallit contact has been penetrated in other parts of the outer Mackenzie Delta. In the Mallik, Taglu and Netserk wells the overlying Kugmallit Sequence rests erosionally on Richards strata, and a distinct Kugmallit basal sandstone is present. North of the Mallik wells, in the Ivik wells, the Richards to Kugmallit succession appears to be a

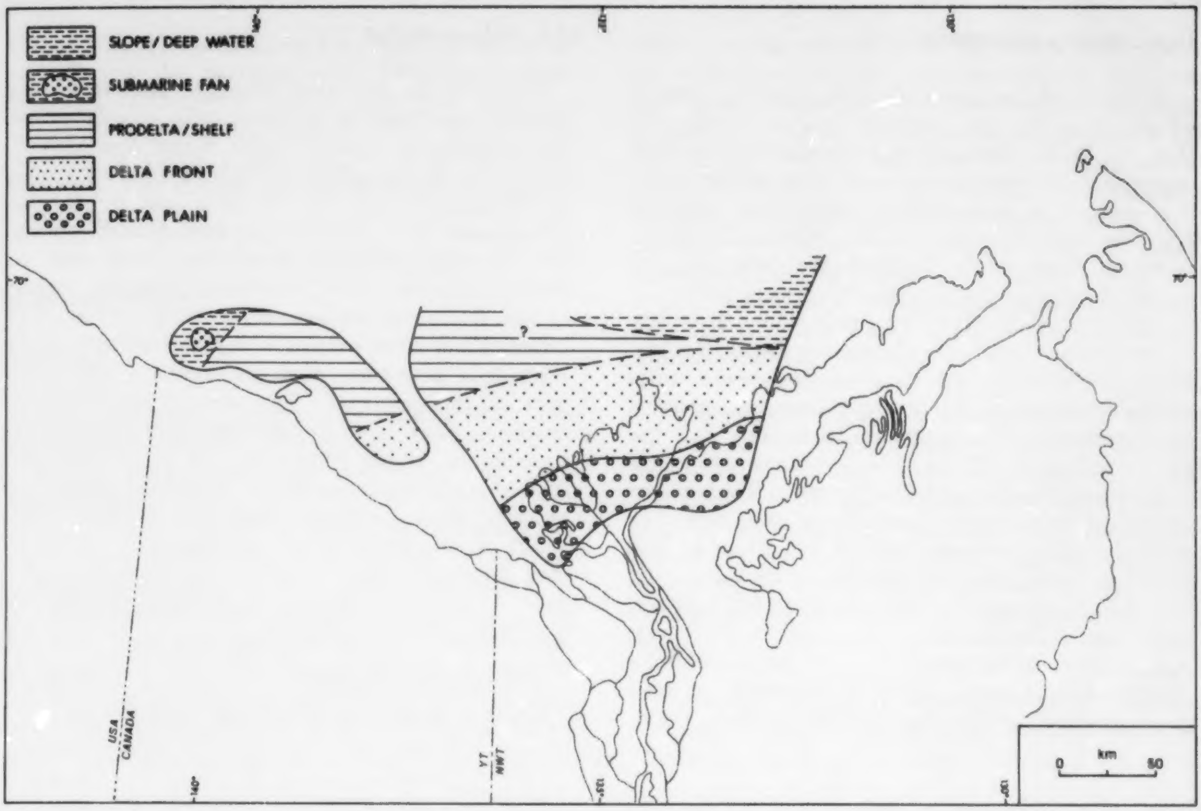

Figure 49. Interpreted Taglu Sequence depositional environments at time of maximum progradation.

gradational change from shales, through thick, coarsening-upward, delta front units, into delta plain sediments (Fig. 50, in pocket). Detailed correlations through this interval can be interpreted as indicating the presence of an unconformity passing through the delta front sediments (Fig. 50), and progressive truncation of delta front sediments toward the Mallik area. If the correlations are correct, then some of the lower sandstone-bearing strata assigned to the Kugmallit Formation (Young and McNeil, 1984) are part of the Richards Sequence. The key to the correlations is the distinct coarsening-upward unit immediately above the basal sandstone identified in the Taglu and Mallik wells (Fig. 50). This interval can be traced into the Ivik wells, as indicated on Figure 50. Other distinct and correlative horizons above and below the basal coarsening-upward unit impose limitations on where correlations can be extended.

Lithotypes in the known Richards Sequence are mostly shale and siltstone. However, local thick sandstone and some conglomerate beds are intercalated within the shale succession under Mackenzie Delta. If the correlations of strata at the Richards/Kugmallit boundary in the Ivik and Kugmallit Bay areas are correct, then the sandstone-bearing succession below the interpreted unconformity would represent deltaic deposits within the Richards Sequence. A thin Richards Sequence at Edlok N-56 contains interbedded very fine to fine grained sandstone and shale (Dietrich et al., 1989).

Only in some of the outer Mackenzie Delta wells and the Edlok N-56 well has the Richards Sequence been fully penetrated. Under Mackenzie Delta and nearshore areas the sequence is 1000 to 2000 m thick (Fig. 51). North of the Issungnak wells the sequence may thin due to pre-Kugmallit shelf-edge erosion. A few of the northernmost wells have made partial penetrations of Richards-equivalent strata (e.g., Kopanaor M-13, Nerlerk M-98), identified by the presence of the diatom *Stellarima* Zone (McNeil, 1990).

Depositional environments

The bulk of the known Richards Sequence consists of prodelta deposits, mostly shale and siltstone (Fig. 52). Within these prodelta deposits there are local occurrences of coarse clastic rocks, up to pebble grade, that appear to be sediment gravity-flow deposits (Glaister and Hopkins, 1974). Within the shale-dominant facies of the Richards Sequence there are abundant diatoms that McNeil (1990) suggested could indicate upwelling of nutrient-rich waters from the bathyal parts of the Arctic Ocean onto the shelf areas. In the Ivik wells, the coarsening-upward units recognized as part of the Richards Sequence represent the only known deltaic deposits. These units are a few tens of metres to 150 m thick, the sandy component comprising 10 to 50 per cent of the units. The majority of the coarsening-upward units appear to be capped by distal delta-front deposits, with a few extending into subaerial, lower delta plain deposits. In the Edlok N-56 well the sandstone-rich Richards Sequence probably represents littoral and inner shelf deposits. Additionally, these sediments yield the foraminifer *Jadammina statuminis*, which is diagnostic of inner shelf, marginal marine environments (McNeil, 1983).

Age and correlation

Strata of the Richards Sequence contain a very distinct assemblage of palynomorphs, dinoflagellates and foraminifers (Staplin, 1976; Young and McNeil, 1984). The dinoflagellates are characterized by species of *Wetzeliella* and the foraminifers by *Haplophragmoides* and several other agglutinated genera. The *Haplophragmoides* Assemblage Zone and the *Haplophragmoides* sp. 2000 Interval Zone are present in the Richards Sequence (McNeil, 1989). The foraminiferal zones overlap with dinoflagellates of the *Wetzeliella* assemblage that are present in the lower part of the sequence. The age of the Richards Sequence, based on palynomorphs, dinoflagellates and foraminifers, is late Middle Eocene to Late Eocene. Within the lower Richards Sequence there are abundant pyrite steinkerns of diatoms (McNeil, 1990), which do not appear to be age-diagnostic, although they occur in a widespread, discrete biostratigraphic zone, have paleoenvironmental significance, and are useful for local correlations.

Correlative strata in mainland Northwest Territories, Arctic Islands, and the Yukon are not well

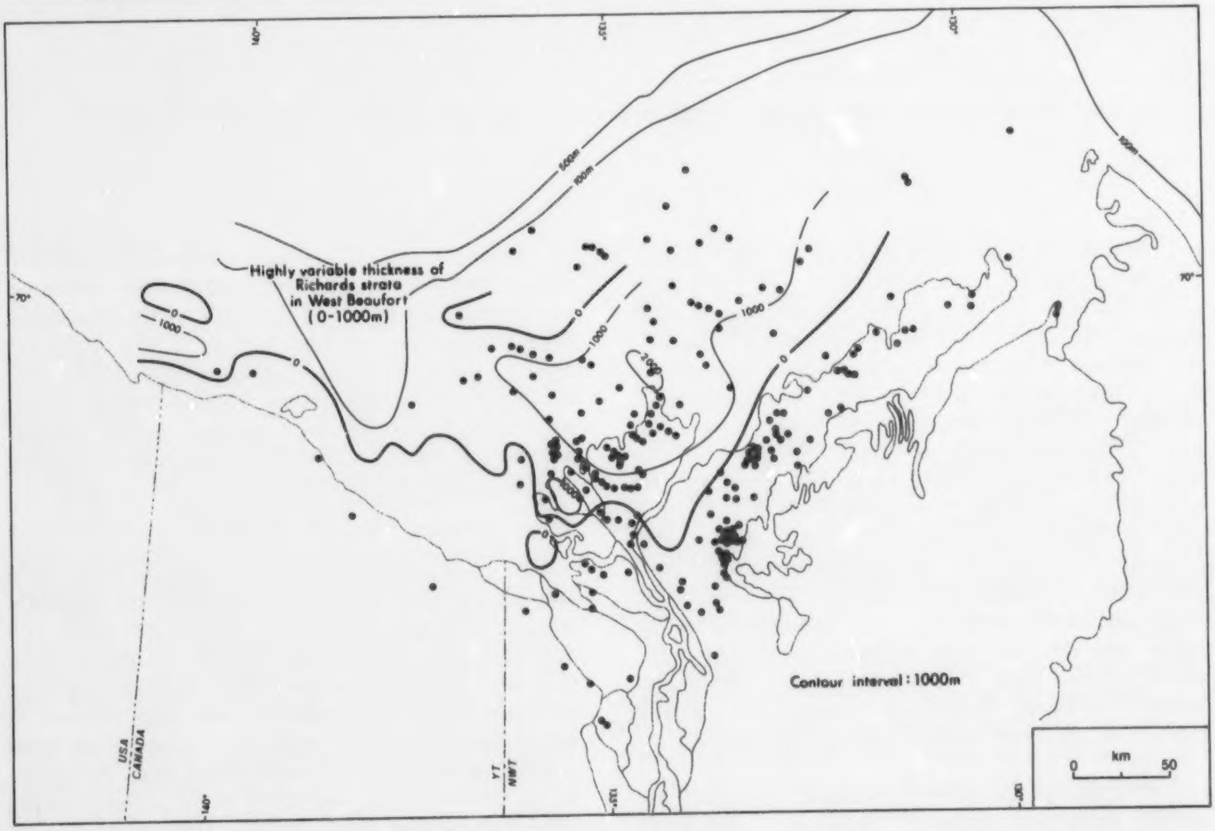

Figure 51. Isopach map, Richards Sequence.

known; the Buchanan Lake Formation in the Arctic Islands may be age-equivalent (Ricketts, 1986). Offshore northeastern Alaska, equivalent strata are certain to be present but have not been identified by drilling. Onshore, part of the Sagavanirktok Formation may contain age-equivalent strata (Bird and Molenaar, 1987).

Kugmallit Sequence

Definition

The Kugmallit Sequence is named after the Kugmallit Formation (Young and McNeil, 1984). Most of the formation represents the landward, deltaic facies within the sequence. Other authors have named Kugmallit strata the Pullen Sand or Delta (Hea et al., 1980; Willumsen and Cote, 1982; Fig. 12). Young et al. (1976) identified the informal "Upper Paleogene Unit B" that became the Kugmallit Formation. The sequence name was first used by Lane and Jackson (1980) and was later adopted and more fully defined by Dietrich et al. (1985). Dietrich et al. (op. cit.) excluded an underlying submarine fan succession that is present only in the far offshore areas and which they named the Kopanoar Sequence. The identification of these beds as a separate transgessive-regressive sequence remains problematic, and for the present discussion we consider the Kopanoar beds to be the lower part of the Kugmallit Sequence. Consequently, the Kugmallit Sequence is redefined to include Kopanoar strata, but, to avoid confusion, we have not used the name Kopanoar (either as a sequence or subsequence). The original definition of the Kugmallit Sequence included only the progradational, deltaic, shelf, and slope deposits overlying the Kopanoar beds.

The Kugmallit Sequence has been identified only in the Beaufort-Mackenzie Basin; it is absent in the Banks-Beaufort Basin. It is best developed in the central part of the Beaufort-Mackenzie Basin and is progressively eroded to the east and northeast. It extends into the western Beaufort-Mackenzie Basin, is present in the Demarcation subbasin and probably extends into Kaktovik Basin, offshore northern Alaska.

The lower boundary is abrupt throughout most of the basin but varies from apparently conformable to an

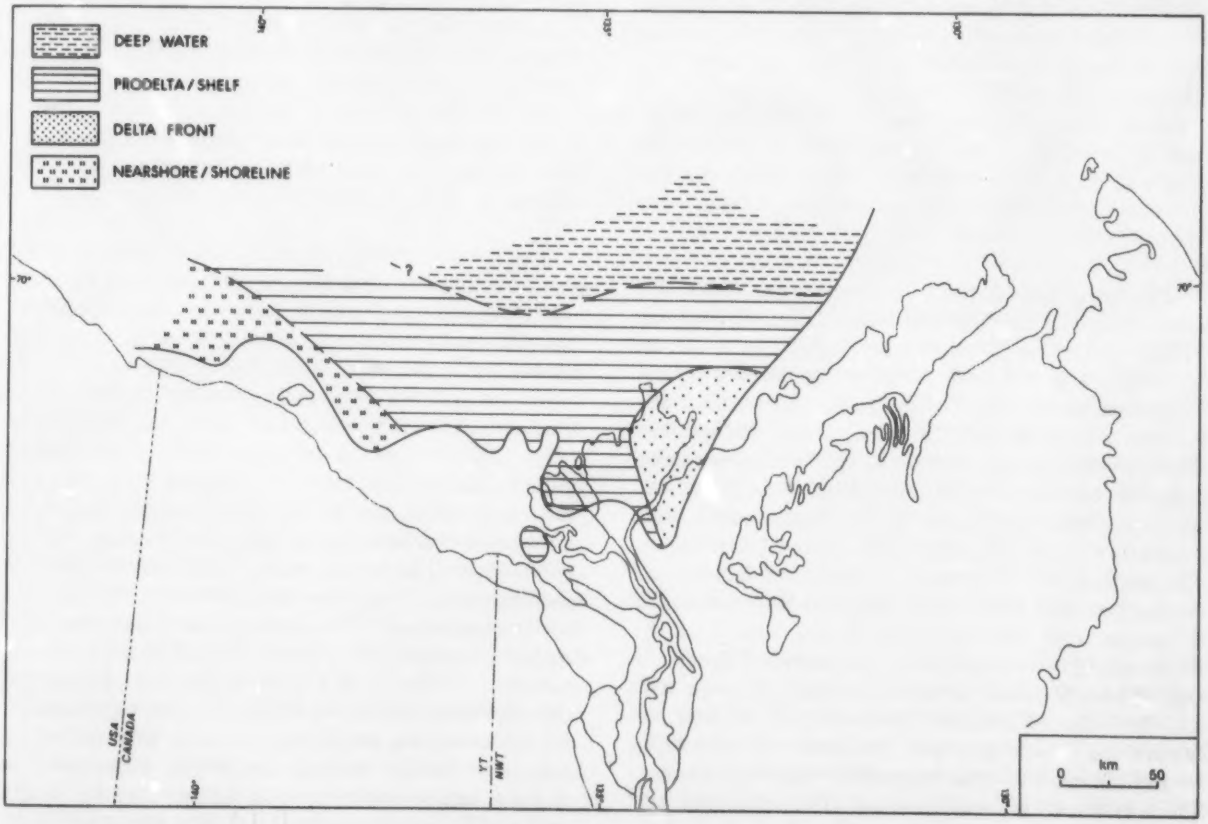

Figure 52. Interpreted Richards Sequence depositional environments at time of maximum progradation.

angular unconformity. Local erosion at the basin margins can be demonstrated from seismic and well data (Figs. 9, 18, 50), as well as some information from outcrop. On seismic records the lower contact generally becomes conformable basinward. Under the Beaufort shelf and Mackenzie Delta areas the sequence is underlain by Richards strata. The upper contact is also abrupt, but only erosional in the central shelf area (Fig. 10). Mackenzie Bay Sequence overlies Kugmallit strata throughout most of the basin, although at the basin margins and some distal basin positions, the younger Iperk Sequence may rest erosionally on Kugmallit beds.

James and Baxter (1988), Morrell and Schmidt (1988), and Baxter and Cheadle (1989) suggested that the Kugmallit succession is divisible into smaller units, at least on a local scale. Six internal unconformities were identified in the Nipterk L-19 and L-19A wells by James and Baxter (op. cit.); however, their regional significance has yet to be tested. Morrell and Schmidt (op. cit.) used reflection seismic and log correlations in the area of Kugmallit delta front facies to identify at least three subsequences in the upper part of the Kugmallit succession. Morrell and Schmidt (op. cit.) demonstrated that their suggested subdivisions could be correlated between a number of wells, but that the chosen boundaries could not be continued into successions dominated by delta plain strata. Baxter and Cheadle (1989) suggested that at least four sequences can be identified in the Kugmallit Formation of the Taglu to Pullen area. However, their brief abstract offers insufficient data to allow their conclusions to be tested.

The only known outcrop of possible Kugmallit strata occurs in the Caribou Hills. There, Price et al. (1980) identified a "white-clay unit", from which Ioannides and McIntyre (1980) recovered a probable Oligocene flora. The "white-clay unit" erosionally overlies Eocene strata of the Aklak Sequence (Reindeer Formation). The probable age of the "white-clay unit" suggests equivalence with the Kugmallit Sequence. Overlying the clay unit are gravels that Young (1978) tentatively identified as Beaufort Formation. Correlation of the gravels is based on lithological similarities with Banks Island Beaufort Formation and a sparse and long-ranging flora identified by Doerenkamp et al. (1976) as Miocene to Pliocene in age. These tenuous correlations must be used with caution. An alternative interpretation is that the white-clay and gravels are part of the same stratigraphic unit — the Kugmallit Sequence (as well as the formation, in this instance). The white-clay and gravels are nonmarine beds and are part of a gently northward dipping succession that appears to extend into Kugmallit strata identified from reflection seismic data. The shallow dip, age, and nonmarine character of the Caribou Hills succession would fit with the known distribution and depositional setting of Kugmallit strata under Mackenzie Delta.

Kugmallit submarine fan deposits

Description and distribution

Under the outer Beaufort shelf, north of the Tarsiut–Amauligak Fault Zone, Dietrich et al. (1985) identified a sequence between the Kugmallit and Richards sequences, which they originally named the Kopanoar Sequence. However, as previously indicated, the Kopanoar succession is included within the Kugmallit Sequence until the significance of these beds in a T-R model is fully understood.

In general, the submarine fan deposits cannot be correlated south of the Tarsiut–Amauligak Fault Zone. However, a major canyon-like feature seen on reflection seismic profiles in the Alerk area is filled with sediment deposited prior to progadation of Kugmallit deltaic and associated strata, and is underlain by Richards or older strata (Fig. 31). The canyon-fill is interpreted as being part of the Kugmallit submarine fan succession, even though direct seismic or biostratigraphic correlations between the Alerk and known Kugmallit submarine fan deposits to the north are not possible.

The seismic expression of the lower contact of the submarine fan succession is variable and includes areas of onlapping reflection patterns on anticlines. Variations in reflection amplitude and continuity commonly occur across the lower contact, but the contrasts are not regionally consistent. The upper contact is locally imaged as a downlap surface (Fig. 10). Few wells have penetrated the entire submarine fan succession; consequently, the log response across the lower boundary has not been adequately characterized. Where penetrated, such as at Havik B-41, the lower boundary is marked by a shift in the velocity gradient. The upper boundary is a downlap surface and has a well defined and consistent sonic and resistivity character change (Fig. 53) that can be recognized in most of the wells that have penetrated the submarine fan strata. In the Alerk area the canyon-fill succession has an obvious erosional lower boundary (Fig. 31). Unlike areas to the north, where the fan deposits are overlain by prograding slope beds, the canyon-fill deposits in the Alerk area are overlain by deltaic beds.

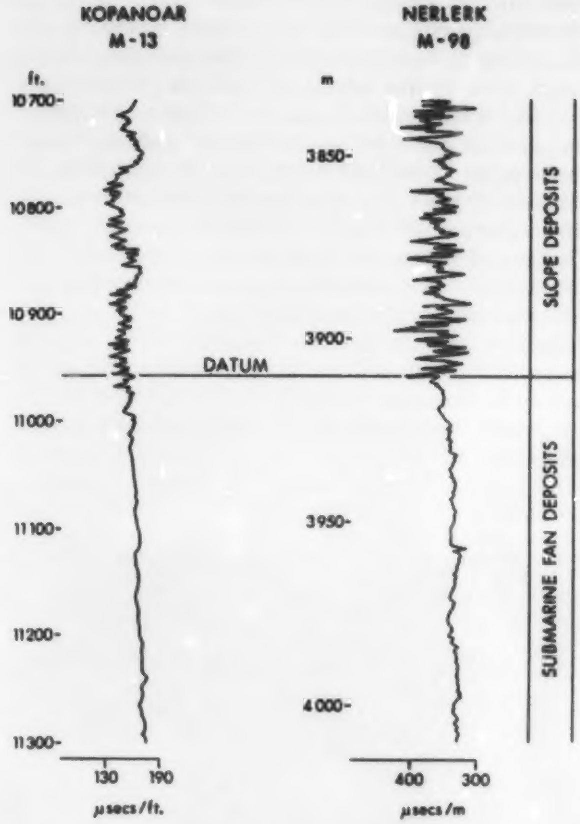

Figure 53. Logs of sonic transit time across the upper boundary of the Kugmallit submarine fan deposits (Kopanoar M-13).

The submarine fan succession is dominated by shale in which there are local sandstone-rich intervals. For example, in the Kopanoar M-13 well there are four such intervals, the uppermost of which is oil bearing (Dixon et al., 1984). Sandstones in the Kopanoar wells are mostly weakly cemented, very fine to fine grained, and consist predominantly of quartz and chert, with a significant proportion of detrital clay (Fig. 54). Even at depths in excess of 3000 m, the sandstones have very little cement — usually some quartz overgrowths. Because of the lack of cement and the overpressured nature of the succession, porosity in some of these sandstones can be very high (25-30 per cent, derived from log analysis). The bulk of the submarine fan succession consists of dark grey to black, silty shale intercalated with fine laminae and thin beds (less than 2 cm thick) of siltstone and and fine grained sandstone. The siltstone and sandstone beds commonly contain small current ripples. Many of the rippled beds are load deformed. Thicker sandstone beds (up to 10 cm) are present but not very common, and usually are finely laminated. In general there is a northward decrease in the amount and number of discrete sandstone beds, although local sandstone units may still be present (e.g., Kenalooak J-94) in outer fan or basin plain environments.

Reflections in the submarine fan deposits are mounded to chaotic in the Kopanoar to Nerlerk area, but become more continuous and subparallel to the north. The mounded character is best seen in sections parallel to regional strike (Fig. 34). Dip sections commonly show the downlapping character of the submarine fan deposits.

The canyon fill in the Alerk area also is mostly shale, although a conglomeratic unit was penetrated and cored in the Alerk P-23 well (cores 4 and 5, 2798-2810.8 m). The poorly preserved core contains well rounded clasts of shale, sandstone and chert in a matrix of sand and granules. Clasts are up to 7 cm in length and are matrix supported. A core from the shale-dominant interval (core 3, 2600-2608.8 m) consists of finely laminated silty to sandy shale. Internal discontinuities and overturned laminae are common. Reflections within the canyon fill are mounded to chaotic (Fig. 31). The dipmeter log through the canyon fill at Alerk P-23 displays distinct patterns. Intervals with uniform dips and dip directions, usually in the northwest to northeast sector, can be readily identified (Fig. 32). A few intervals have dips toward the south and southwest.

The few fully penetrated sections of the Kugmallit submarine fan succession are in the order of 1000 m in thickness. However, seismic correlations clearly indicate that the thickest development occurs southeast of the Kopanoar wells, where upwards of 2500 m of strata may be present (Fig. 55). The succession thins depositionally northward and westward and appears to be absent or very thin in the west Beaufort (Fig. 55). About 600 to 700 m of strata have been penetrated at Alerk P-23 but the canyon fill and slope sediments to the north may be upward of 1000 m thick.

Depositional environments

The submarine fan interpretation is based on the basinward position, lithological character and seismic expression, all of which indicate a deep water setting. The extensive erosional lower boundary points to a period of major relative, and perhaps absolute, sea-level drop. Erosion of Richards and older strata indicates shelf edge erosion prior to and during deposition of the submarine fan beds. The mounded reflection patterns grading northward into subparallel, continuous reflections are typical of submarine fan deposits, such as those described from the North Sea by Heritier et al. (1979, 1981). This change in reflection character is interpreted as representing a northward change from inner and middle fan to outer fan and basin plain. The canyon at Alerk P-23 appears to have been one of the main feeder canyons. Similar erosional features occur to the northeast of the Alerk area.

To date, the penetrated part of the submarine fan succession is in the mid to outer fan; consequently, there has not been a great amount of sandstone encountered. At Kopanoar M-13 the three deepest sandy intervals consist of thick, fining-upward intervals (Fig. 33), whereas the uppermost sandy interval consists of several thinner, stacked, fining-upward units (Dixon et al., 1984). In the nearby Kopanoar 2I-44 well the lower three sandstone bodies were not encountered, and although an upper sandstone interval was present, seismic correlations suggest that there are no continuous sandstone bodies between the 2I-44 and M-13 wells. Furthermore, the interval in 2I-44 equivalent to the upper sandstone in M-13 did not yield hydrocarbons. Dixon et al. (1984) interpreted the sandstone bodies in M-13 and 2I-44 as deposits of channels on the inner to mid fan. The lack of continuity of the sandstone bodies in an east-west direction between the two Kopanoar wells, and the mapped northerly orientation (unpublished data) of the mounds (channel levees?) in the vicinity of the Kopanoar wells indicate a northerly trend for the channels.

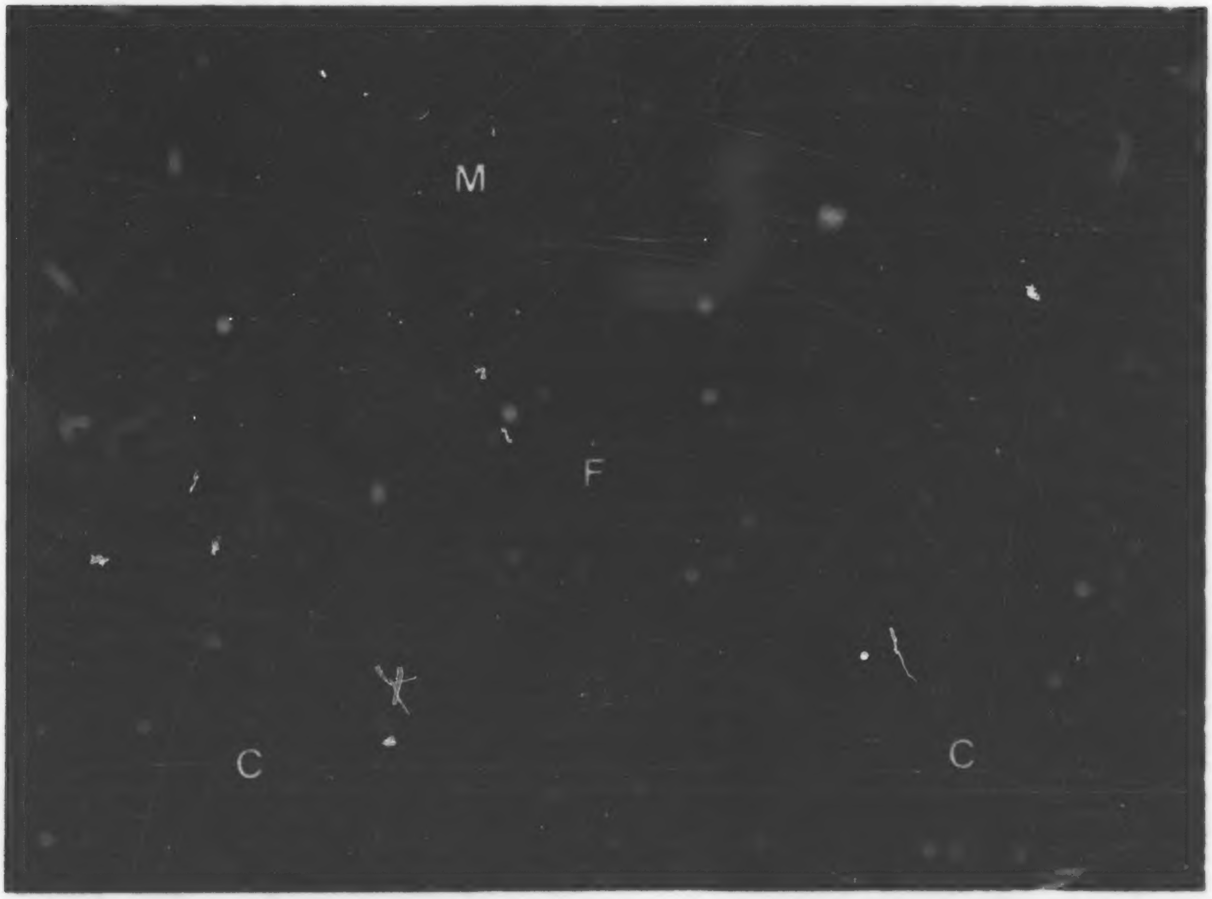

Figure 54. SEM photomicrograph of a typical sandstone from the Kugmallit submarine fan succession (Kopanoar M-13 well, cutting sample between 3532 and 3560 m). Note the lack of cementation and open pore network. F, feldspar; C, chert; M, mica. ISPG photo. 1728-4.

The Kugmallit submarine fan appears to have been deposited as a single, large complex (Fig. 56), fed by north to northwesterly trending submarine canyons. Its position within the basin appears to have been controlled by the intersection of the east-west trending Tarsiut–Amauligak Fault Zone and northeast trending Outer Platform Hinge Line, immediately basinward of which is located the submarine fan depocentre. It seems most probable that sea level dropped substantially to create the conditions necessary for shelf edge erosion and resedimentation.

Age and correlation

Kugmallit submarine fan strata tend to be barren, or sparsely fossiliferous, so dating of the strata by indigenous elements is not accurate. The few fossils that have been identified suggest a Late Eocene or Oligocene age (Dixon et al., 1984–their sequence 5 in the Kopanoar M-13 well). This is consistent with the known stratigraphic position of the fan deposits between two better dated successions, the Middle to Late Eocene Richards Sequence below and the Oligocene Kugmallit deltaic to slope deposits above. The stratigraphic position suggests a Late Eocene or Early Oligocene age.

Kugmallit progradational deposits

Description and distribution

Lithotypes in Kugmallit progradational deposits range from conglomerates and gravels under Mackenzie Delta, to sandstone-dominant under the Beaufort Sea inner shelf, to shale-dominant in the farthest offshore areas. Thin beds of lignite are present in the "white-clay unit" at Caribou Hills, but in general, coal beds are uncommon in Kugmallit deltaic strata. Amber is a common constituent of the Kugmallit sandy facies. The succession is estimated to range up to 3000 or 4000 m in thickness in the Issungnak area (Fig. 57). Kugmallit strata have been eroded from the Blow River and Herschel highs but are present in Demarcation subbasin. In Demarcation

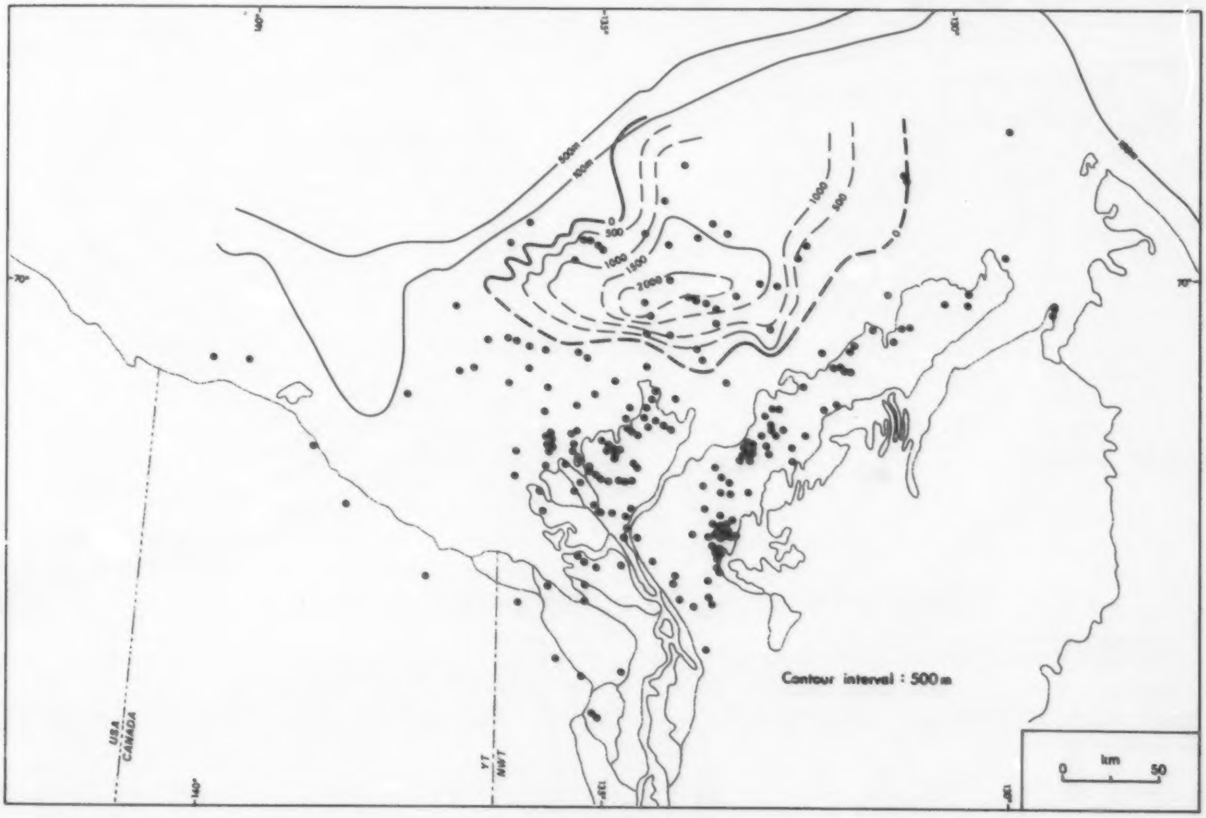

Figure 55. Isopach map, Kugmallit submarine fan deposit.

subbasin, the Kugmallit Sequence consists of weakly consolidated shale interbedded with thin beds of fine grained sandstone and, locally, coarser sandstone or pebbly sandstone. In the Edlok N-56 well, two coal-bearing intervals were penetrated, between 620 and 650 m and 1010 and 1045 m. The northern and southern limits of the Kugmallit Sequence are erosional edges below the sub-Iperk unconformity.

Depositional environments

The Kugmallit progradational deposits contain a range of depositional facies, from delta plain to basinal. Deltaic deposits are centred over the Taglu to Issungnak areas. Lateral to and basinward from these areas are prodelta and deep water deposits (Fig. 58). Under Mackenzie Delta and the nearshore areas, delta plain deposits are prevalent in the sequence. Northward the sediments grade into lower delta plain and delta front facies. At its maximum progradation, the Kugmallit delta deposited delta front sediments to the shelf edge. Part of the Kugmallit shelf edge was situated approximately parallel to the Tarsiut-Amauligak Fault Zone (Fig. 10). North of the fault zone are slope-to-basinal deposits, dominated by shale. The deep water deposits have many similarities with the Kugmallit submarine fan succession on reflection seismic profiles: hummocky reflections proximal to the fault zone, becoming subparallel distal to the fault zone. However, unlike the submarine fan deposits, the bottomset beds of the Kugmallit progradational succession appear to be shalier, shelf-margin-fed deposits. East and west of the delta depocentre, prodelta/shelf shale becomes more prevalent in the succession. At Tarsiut, sandy intervals within the shale-dominant Kugmallit succession represent the distal, submarine part of delta lobes. On some reflection profiles these sandy units are seen as intervals of shingle-like reflections (Fig. 18).

Age and correlation

The Kugmallit progradational deposits contain foraminifers of the *Cancris subconicus* and *Turrilina alsatica* Interval Zones (McNeil, 1989) and a flora similar to that found in the upper Richards Sequence (McIntyre, 1985). The foraminifers indicate an Oligocene age (McNeil, op. cit).

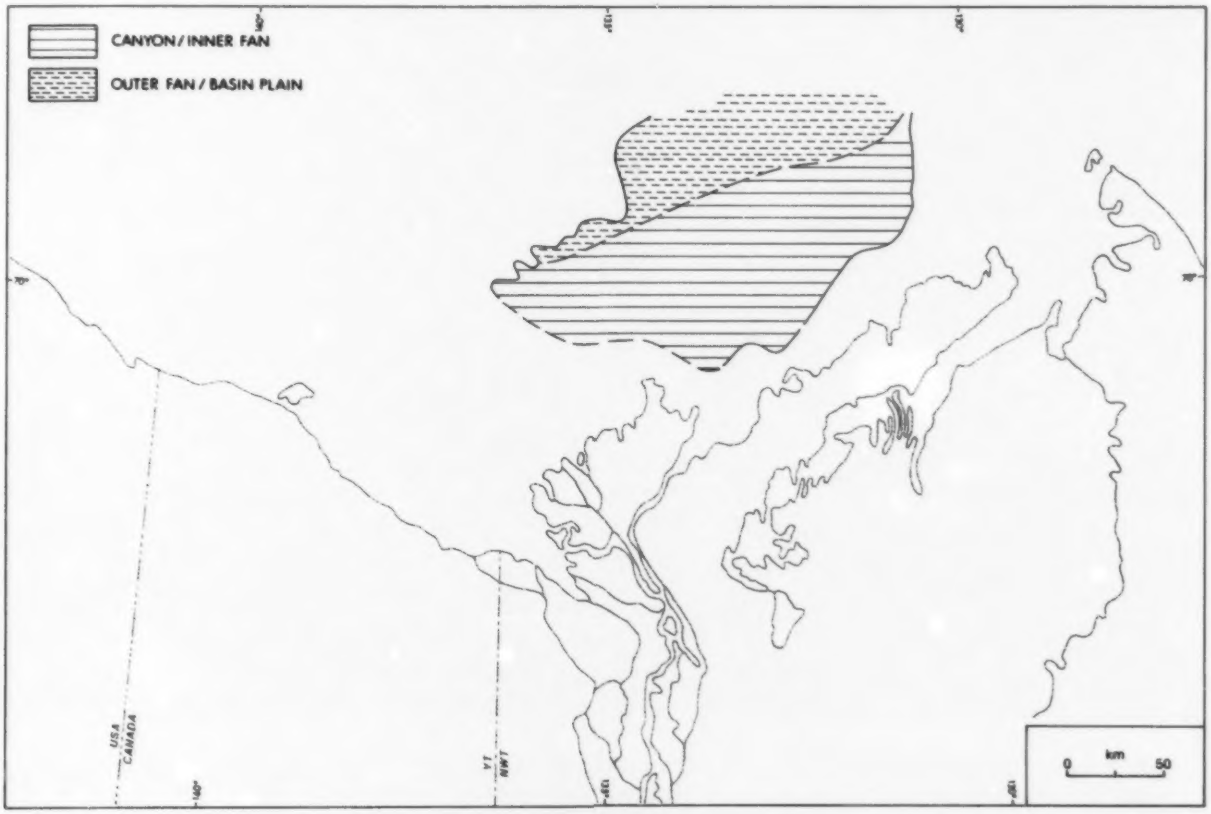

Figure 56. Interpreted depositional environments on the Kugmallit submarine fan.

Oligocene strata in northern Canada are poorly known. Miall (1986) indicated that the uppermost strata of the Eureka Sound Group were possibly Oligocene, based on very tenuous data. Seismic correlations indicate that Kugmallit strata extend into the Kaktovik Basin of the U.S. Beaufort Sea. In northeastern Alaska, age-equivalent strata may be present in part of the Sagavanirktok Formation (Bird and Molenaar, 1987).

Mackenzie Bay Sequence

Description and distribution

The Mackenzie Bay Sequence is named after the Mackenzie Bay Formation (Young and McNeil, 1984) to which it is essentially equivalent (Fig. 12). However, unlike Young and McNeil (op. cit.) we do not consider their Beaufort Formation to be entirely coeval with Mackenzie Bay strata. Young and McNeil (1984) identified the Beaufort Formation between the Kugmallit and Mackenzie Bay formations, separated from the underlying Kugmallit Formation by an unconformity. Young and McNeil's (op. cit.) reason for identifying the Beaufort Formation appears to be based on Staplin's (1976) identification of a major floral change in the Taglu G-33 well, which he interpreted as being the result of an unconformity. Also, some wells in the Taglu to Ivik area of the Mackenzie Delta contain foraminifers of the Miocene *Asterigerina staeschi* Interval Zone (typical of the Mackenzie Bay Sequence) which occurs just below the Iperk Sequence (Nuktak Formation), but well above the unconformity identified by Staplin (op. cit.) and Young and McNeil (op. cit.). The floral change identified by Staplin (op. cit.) coincides with a significant vertical facies change from interbedded sandstone and shale below to predominantly sandstone and conglomerate above. Young and McNeil (op. cit.) suggested that the Beaufort Formation was, in part, laterally equivalent to Mackenzie Bay Formation shales and interdigitated with Mackenzie Bay strata north of the Ivik area. Initial seismic correlations suggested that the Beaufort Formation (sensu Young and McNeil, op. cit.) was part of the Kugmallit Sequence (Dietrich

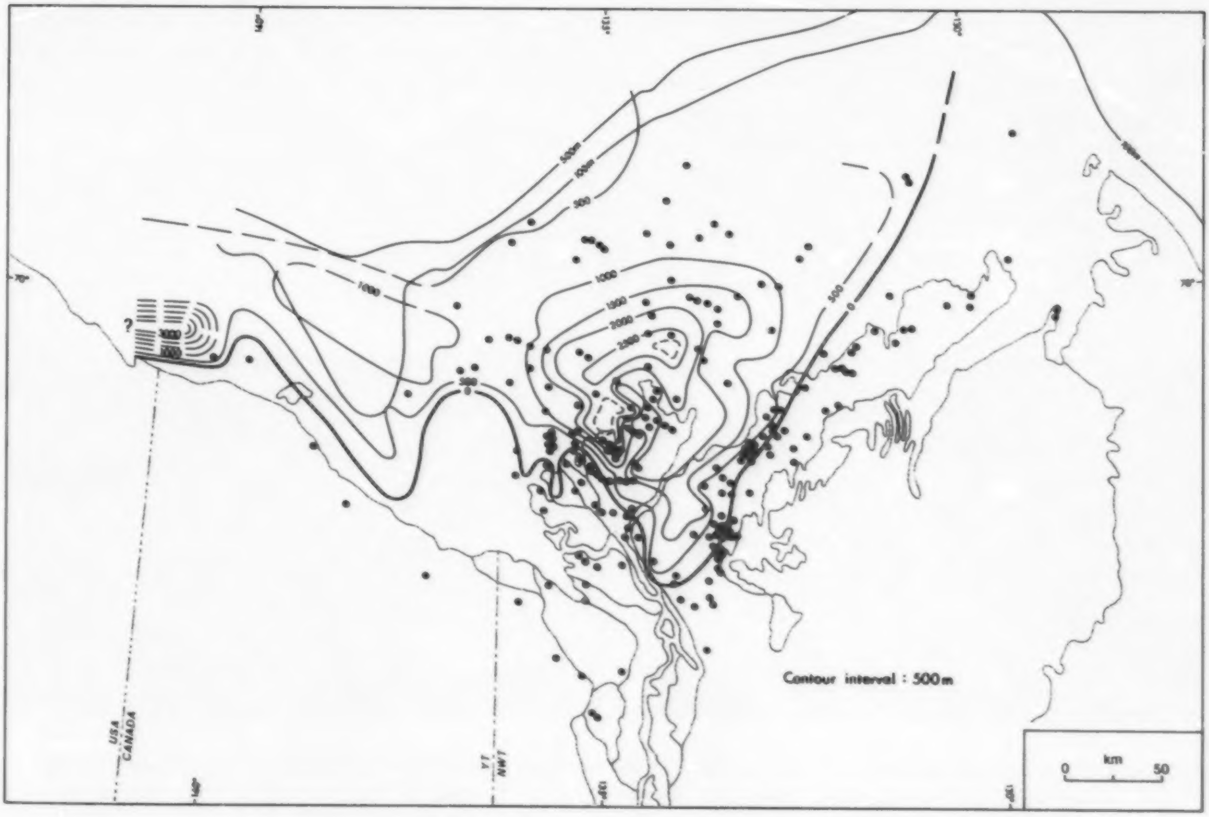

Figure 57. Isopach map, Kugmallit progradational deposits.

et al., 1985; Dixon et al., 1985). Re-evaluation of seismic and biostratigraphic data indicates that the upper 200 to 300 m, the *Asterigerina staeschi*-bearing part of the sandstone-rich Beaufort Formation, may be a basin margin facies of the Mackenzie Bay Sequence (Fig. 50). The exact depth to the base-of-Mackenzie Bay unconformity in the wells of the Taglu–Ivik area is difficult to identify on reflection seismic or from well data.

The lower contact of the Mackenzie Bay Sequence is erosional over local structural highs (e.g., Adgo Anticline) and along paleoshelf slopes north of the Tarsiut–Amauligak Fault Zone (Fig. 10). The upper contact is mostly conformable with Akpak strata, although shelf margin truncation of Mackenzie Bay strata is evident on some seismic profiles (Fig. 10). The outer shelf and slope portions of the Mackenzie Bay Sequence are characterized by high amplitude reflections and well developed clinoforms, and are good examples of high amplitude seismic facies developed in shale-dominant shelf sediments. Where Mackenzie Bay shelf strata rest on Kugmallit deltaic deposits, there is a marked lithological contrast between Mackenzie Bay shale and Kugmallit sandstones.

Shale is the dominant rock type in the central Beaufort area, where there are the most penetrations of the sequence. A common characteristic of these shales is the abundance of pyrite, commonly in the shape of straight or branching rods. These pyrite rods are generally 1 to 2 mm in diameter and usually only a few millimetres long (Fig. 59). Their origin is unknown, although it is possible that they represent replacement of burrow-fill material. They are so characteristic of the sequence that they can be used to identify it with a fair degree of confidence in the absence of other data. However, in places the pyrite rods do extend into the overlying Akpak and underlying Kugmallit sequences and cannot be relied upon entirely. Sand and silt grains are a common component of the cuttings in the shale successions indicating the presence of intercalated, thin, sandstone and siltstone beds. In the Netserk and Uviluk wells there are several sandstone units that are thick enough to register on logs. Under the outer

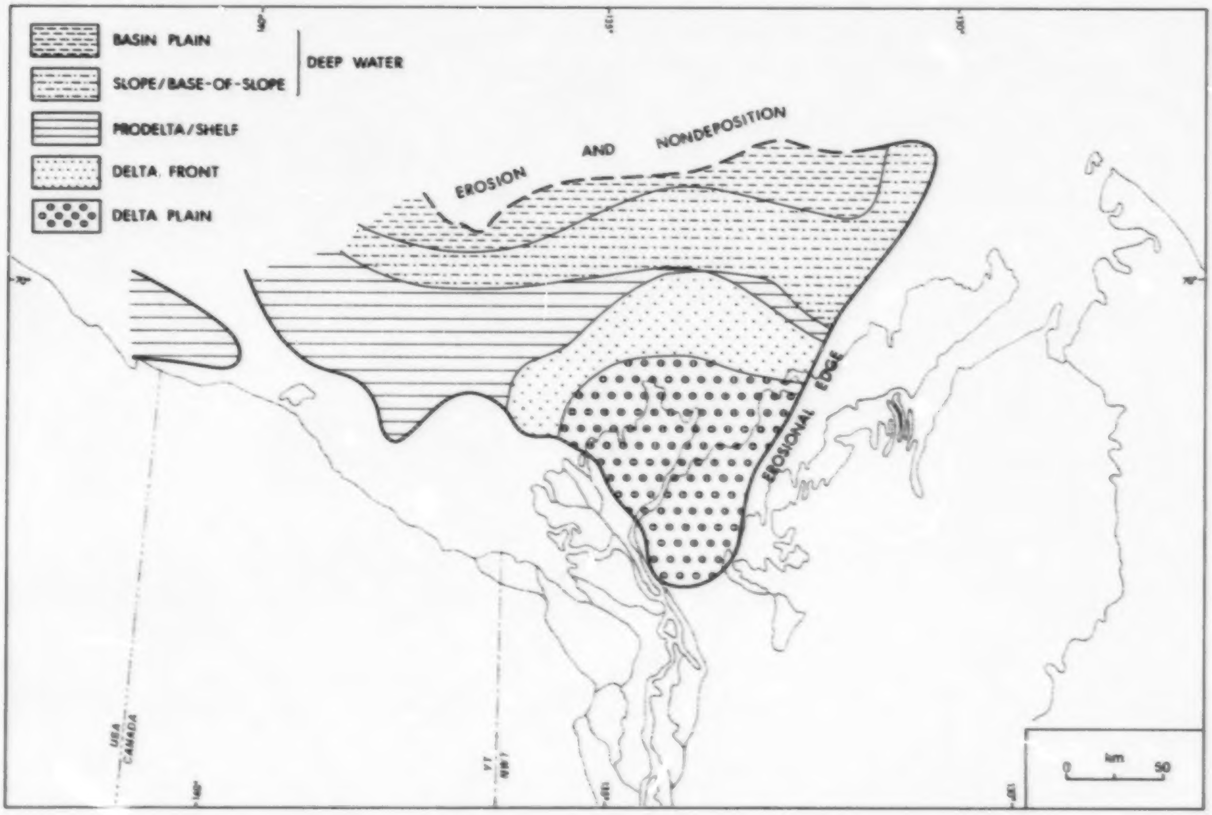

Figure 58. Interpreted depositional environments during Kugmallit progradation.

Mackenzie Delta, in the Taglu to Ivik wells, there is a thin remnant of the Mackenzie Bay Sequence between the Iperk and Kugmallit sequences that is sandstone-rich. These locally preserved sandy successions have been identified as Mackenzie Bay Sequence on the basis of occurrences of foraminifers from the *Asterigerina staeschi* Interval Zone (see Fig. 6 in Young and McNeil, 1984, where the foraminifers are referred as *Cibicides* spp.). Log signature and lithological characteristics are very similar to those of the enclosing strata and the exact boundaries of Mackenzie Bay strata in these wells is speculative (Fig. 50).

Mackenzie Bay strata underlie most of the Beaufort shelf; their southern limit is a truncation edge below the sub-Iperk unconformity. Nowhere are Mackenzie Bay strata known to be exposed in the Yukon or adjacent Northwest Territories. Their southern subcrop edge just reaches the outer part of Mackenzie Delta (Fig. 60). Where the Demarcation subbasin has been penetrated by the Edlok N-56 well, the Mackenzie Bay Sequence is seen to be present as part of the sediment fill. Under the central Beaufort shelf the sequence expands basinward from a few hundred metres in thickness to about 1000 m in the vicinity of North Issungnak L-86. However, the thickest development occurs in the western part of the Beaufort–Mackenzie Basin where up to 2000 m, or more, of section are present (Fig. 60).

Depositional environments

The prevalence of clinoform reflections and shale dominance point to the known parts of the sequence being dominated by prodelta/shelf, slope, and deep water deposits (Fig. 61). Extensive tracts of deltaic strata have not been identified to date, although the sandstone-rich interval in the Taglu to Ivik area could indicate an erosional remnant of a delta depocentre. The thin sandstone units at the base of the sequence in the Netserk wells appear to be transgressive beds, whereas those within the sequence at Uviluk P-66 are deep-water deposits. The fining- and coarsening-upward trends and regional setting of the P-66 sandstone intervals suggest a slope or submarine fan setting.

Age and correlation

Mackenzie Bay strata contain foraminifers of the *Cibicides* Assemblage Zone, and the upper part of the *Turrilina alsatica* and the whole of the *Asterigerina staeschei* Interval zones (McNeil, 1989), as well as long-ranging palynomorphs. The foraminifers indicate an age of Late Oligocene in the lower part of the sequence and Early to Middle Miocene in the upper part. Although the flora is long ranging, sufficient numbers of dinoflagellates have been recovered to indicate a Miocene age (McIntyre, 1985).

Miocene strata are poorly documented in northern Canada, although the Beaufort Formation of Banks Island has been indicated as being Miocene and could be correlative with the Mackenzie Bay Sequence. However, the age of the Beaufort Formation is not well defined and ages as old as Early Miocene to as young as Late Miocene have been suggested (Hills, 1969; Hills and Fyles, 1973; Hills et al., 1974) for

Figure 59. SEM photomicrographs of pyrite rods from the Mackenzie Bay Sequence in the Natiak O-44 well. A: general view of a pyrite rod; B: close-up of sample in photograph A, illustrating the octahedral crystals of pyrite; C: close-up of a different sample, illustrating the cubic nature of the pyrite crystals. ISPG photos. 3043-1, 6, and 7, respectively.

Banks Island strata. If the Beaufort Formation on Banks Island is Early or Middle Miocene, then it is probably correlative with Mackenzie Bay strata; if Late Miocene, then it is more likely to be correlative with the Akpak Sequence. Possible equivalents of the lower Mackenzie Bay Sequence may be present in the Nuwok Member of the Savaganirtok Formation at Carter Creek, on the Alaskan North Slope (approximately 150 km west of the Yukon–Alaska border). The Nuwok Member contains foraminifers of the upper part of the *Turrilina alsatica* Zone (McNeil and Miller, in press). Seismic correlations across the Yukon–Alaska offshore border indicate that Mackenzie Bay strata extend into offshore northeastern Alaska.

Akpak Sequence

Description and distribution

Willumsen and Cote (1982) introduced the term Akpak Delta for a succession of strata between the Kugmallit (their Pullen) and Iperk (their Beaufort) sequences (Fig. 12). However, the Akpak Delta includes two sequences, the lower of which is equivalent to the Mackenzie Bay Sequence and the upper, which will be referred to as the Akpak Sequence (the Akpak Sequence corresponds to the hachured area on Willumsen and Cote's Figure 13, op. cit.). On Banks Island the Beaufort Formation may be equivalent to the Akpak Sequence, but because of extensive erosion of Miocene strata in the area of Amundsen Gulf, no direct seismic correlation can be made between the two areas.

In the Beaufort–Mackenzie Basin, the Akpak Sequence abruptly overlies older strata and is unconformably overlain by the Iperk Sequence. Throughout much of the central Beaufort and the outer shelf areas of the west Beaufort, the Akpak Sequence is characterized by the presence of clinoforms. In the south-central part of the Beaufort–Mackenzie Basin, the Akpak Sequence is characterized seismically by low amplitude to reflection-free intervals, in marked contrast to more reflective enclosing strata (Fig. 10). The sequence becomes more

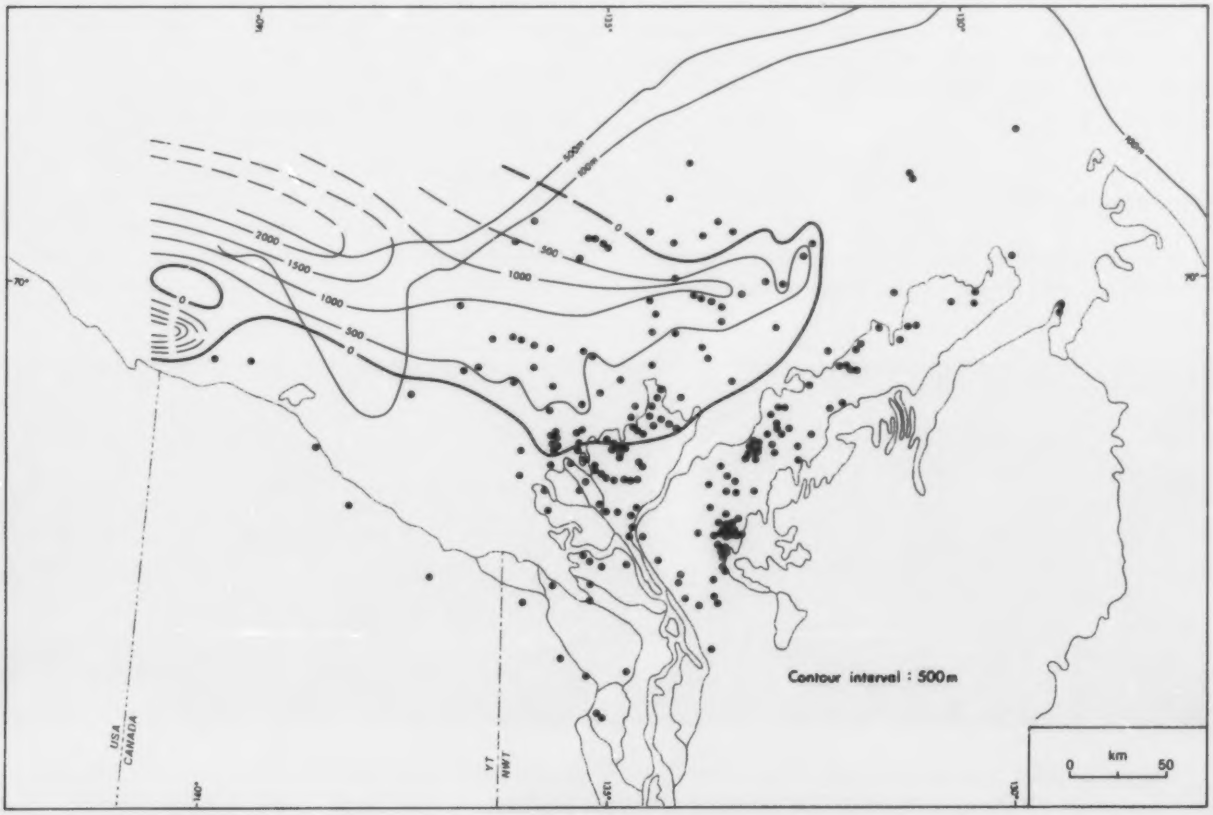

Figure 60. Isopach map, Mackenzie Bay Sequence.

reflective toward the western part of the basin, and the seismic differentiation between Akpak and Mackenzie Bay strata is less dramatic. The upper boundary is erosional throughout most of the basin, and the sequence is progressively truncated in a landward direction. As previously noted, the lower bounding unconformity is locally erosional along paleoshelf margins and slopes (Fig. 10). Nowhere is the Akpak Sequence exposed.

The Beaufort Formation on Banks Island erosionally overlies the Eureka Sound Formation and in places is erosionally overlain by the Worth Point Formation (Miall, 1979; Vincent et al., 1983). Offshore Banks Island, the Beaufort Formation (?Akpak Sequence) generally is not recognized and Iperk strata erosionally overlie the Aklak Sequence (Fig. 8).

The penetrated Akpak Sequence is predominantly shale interbedded with thin siltstone and sandstone units, commonly too thin to register on logs but the presence of which is inferred from the abundance of sand and silt grains in cuttings. Shale is the dominant rock type in the deep water, slope and shelf settings. On Banks Island the possibly correlative Beaufort Formation is characterized by gravels, coarse sands, and lignite beds.

Akpak strata in the central Beaufort area thicken from an erosional edge to about 1000 m in the vicinity of the North Issungnak L-86 well, and to an estimated 1000 m or more in the western Beaufort Sea (Fig. 62). Strata thin in the basinal areas and commonly are difficult to segregate from Mackenzie Bay strata. It is possible that there may be some Akpak strata in Demarcation subbasin, although there is a lack of wells and direct seismic correlations to known Akpak strata to confirm this speculation. The Beaufort Formation is thin on Banks Island, ranging from 10 m to a possible 490 m (Miall, 1979).

Depositional environments

The bulk of the known Akpak Sequence consists of prodelta/shelf, slope, and basinal deposits (Fig. 63).

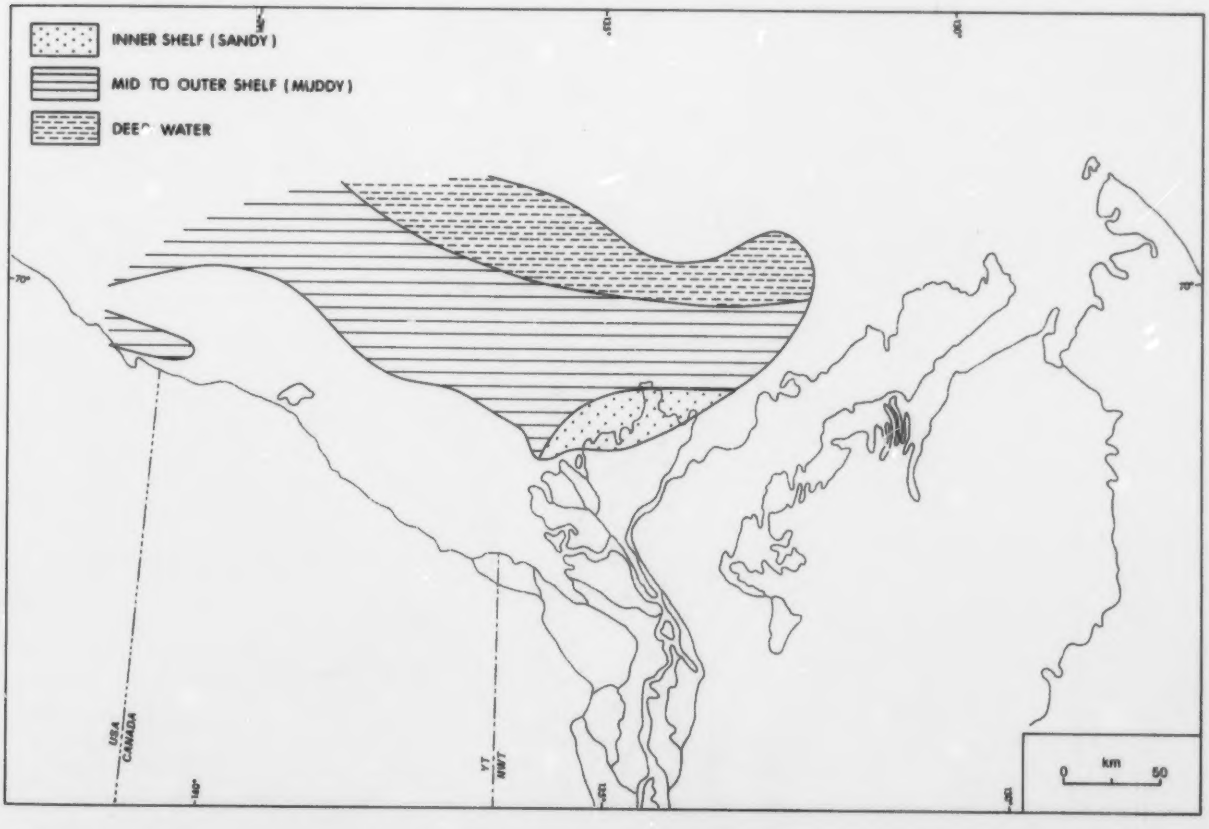

Figure 61. Interpreted Mackenzie Bay Sequence depositional environments at time of maximum progradation.

Clinoform reflections are widespread in the outer shelf areas of Beaufort Sea and the bottomset reflections are subparallel and discontinuous (Figs. 6, 10). The basinal deposits of the Akpak Sequence do not appear to contain many thick sandstone beds. Sandy deltaic or littoral deposits have not been identified to date in the Beaufort-Mackenzie Basin, but it is possible they are present in parts of Demarcation subbasin. On Banks Island the Beaufort Formation has been interpreted as being mostly fluvial in origin (Miall, 1979).

Age and correlation

Akpak strata contain foraminifers of the *Cibicidoides* sp. 800 Interval Zone (McNeil, 1989). Palynomorphs and dinoflagellates are similar to those found in the Mackenzie Bay Sequence (McIntyre, 1985), although Bujak and Davies (1981) recorded Late Miocene dinoflagellates from Akpak strata in the Kopanoar M-13 well. The indigenous fossils indicate a Miocene age, probably Late Miocene.

Equivalent strata are traceable on reflection seismic profiles into offshore northeastern Alaska. On the North Slope of Alaska, part of the Sagavanirktok Formation contains Miocene beds (Bird and Molenaar, 1987), some of which could be equivalent to the Akpak Sequence.

Iperk Sequence

Description and distribution

The Iperk Sequence is named after the Iperk Group (Jones et al., 1980; Fig. 12). Jones et al. (1980) defined the Iperk Group as those strata extending from the sea bed to a prominent regional unconformity. However, the Iperk Sequence does not include some of the uppermost beds in this succession, which belong to the Pleistocene-Holocene Shallow Bay Sequence, although it is commonly difficult to separate Iperk from Shallow Bay strata. Jones et al. (op. cit.) cited Ukalerk C-50 (Fig. 22A) as the type well for the Iperk Group,

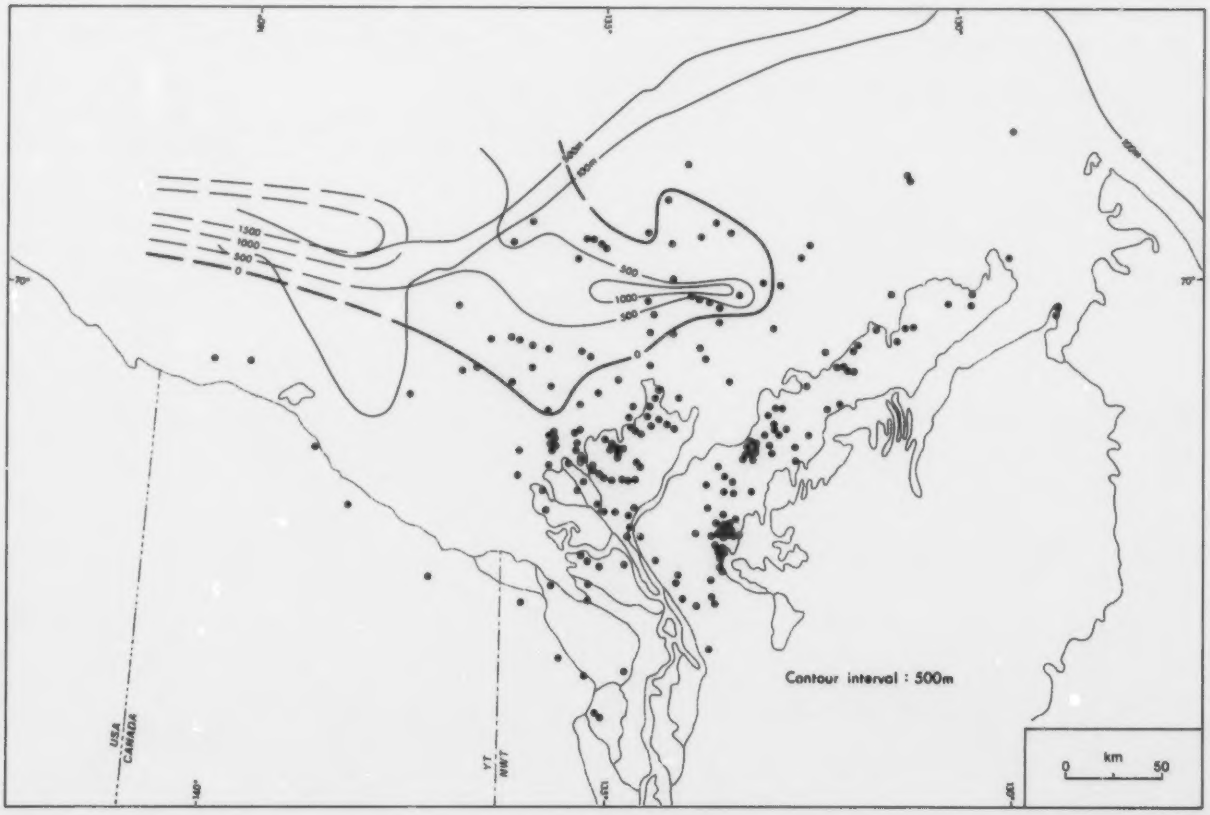

Figure 62. Isopach map, Akpak Sequence.

between the base of the glory hole to log depth 1568 m (5144 ft.). McNeil et al. (1982, p. 2) identified the basal unconformity at 1571.5 m (5156 ft.) in the same well. Jones et al. (op. cit.) recognized that the Iperk succession contained several vertical facies changes, hence the definition as a group rather than a formation. The identification of the Iperk succession as a sequence negates the need to use lithological criteria for stratigraphic divisions. Young and McNeil's (1984) Nuktak Formation is the basin-margin equivalent of the Iperk Sequence. The base of the Iperk Sequence is a major erosional unconformity that can be traced throughout the Beaufort-Mackenzie and Banks-Beaufort basins.

The Iperk Sequence has been identified as the Beaufort Formation or sequence in the Beaufort-Mackenzie Basin by a number of authors (Fig. 12; Hea et al., 1980; Lane and Jackson, 1980; Willumsen and Cote, 1982). The Beaufort Formation was the name originally used for the youngest, but poorly dated, succession of sands and gravels on Prince Patrick Island in the Arctic islands (Tozer, 1956). Lithologically similar strata on Banks Island were correlated with the Beaufort Formation and dated as Miocene (Hills, 1969; Hills and Fyles, 1973; Hills et al., 1974). Gravels at the north end of Caribou Hills (Young et al., 1976, p. 36; Price et al., 1980) and in Anderson Basin (Yorath et al., 1975) also were identified as Beaufort Formation, based on lithological similarities and some meagre paleontological information (Doerenkamp et al., 1976). To add further confusion, Norris (1981d) mapped the gravels at Storm Hills (north of Inuvik) as Beaufort Formation. The Storm Hills lie just east of Caribou Hills and the gravels overlie those of Caribou Hills (also identified as Beaufort Formation by other authors). As previously argued in the section on the Kugmallit Sequence, the Caribou Hills gravels are most likely part of the Oligocene Kugmallit Sequence. The plethora of confused and confusing correlations warrants the discontinuation of the term Beaufort Formation/Sequence in the Beaufort-Mackenzie Basin.

The Storm Hills gravels rest on a low-angle (1-2°) planar surface dipping to the northwest, which appears

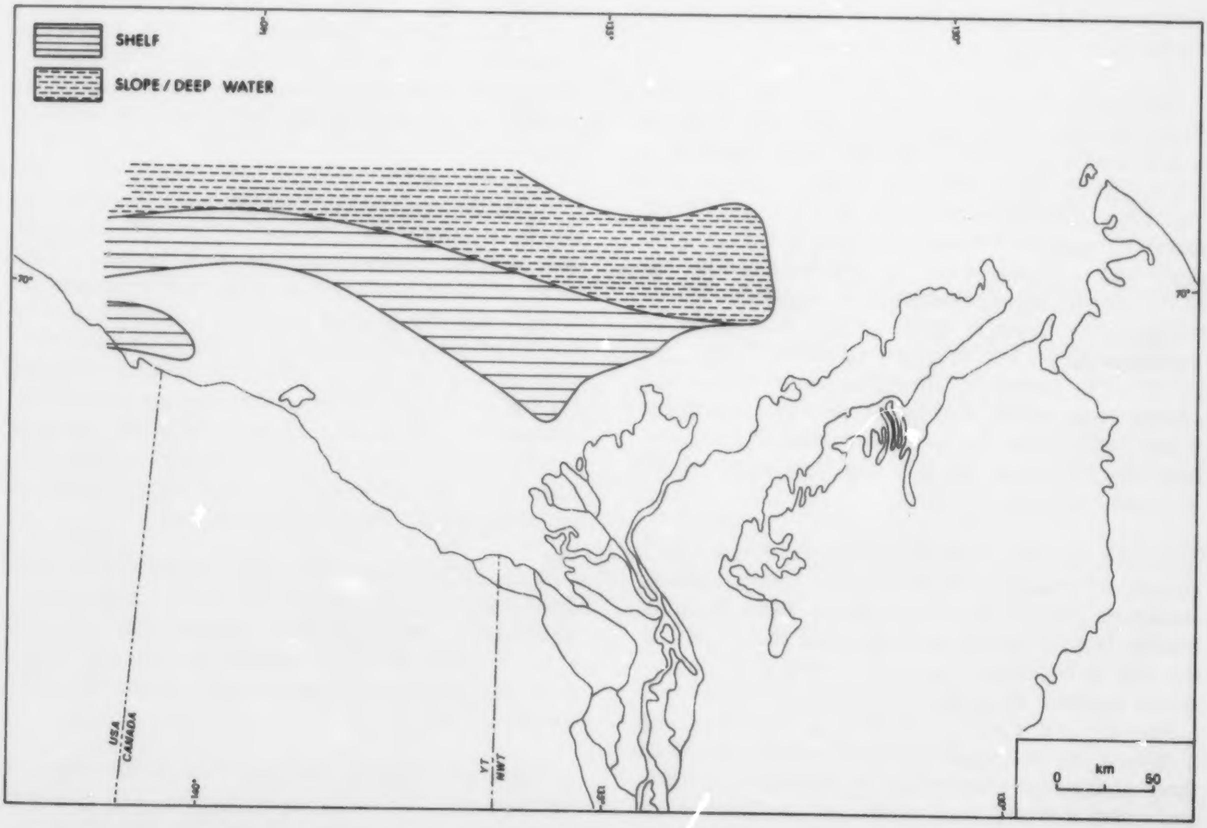

Figure 63. Interpreted Akpak Sequence depositional environments at time of maximum progradation.

to be part of an exhumed unconformity surface. This surface appears to project into the sub-Iperk unconformity in the offshore areas. It seems probable that the Storm Hills gravels are part of the Iperk Sequence.

Along the northern Yukon coast, sands and gravels of the Pleistocene Herschel Island Formation (Naylor et al. 1972; Johnson et al. 1976) are exposed. Young and McNeil (1984) considered Herschel Island strata to be younger than the Nuktak Formation and implied that they were deposited during the glacial/interglacial periods of the Pleistocene. Young and McNeil (op. cit.) included glacial tills within the formation, yet the earlier descriptions clearly indicate that a Wisconsin till overlies the formation (Hughes, 1972; Johnson et al., 1976). Furthermore, the Herschel Island strata have been deformed by ice push. Clearly, the Herschel Island succession is either a preglacial or an interglacial deposit. Johnson et al. (op. cit.) suggested that the formation was equivalent to near-surface sediments under Mackenzie Delta, basing their conclusion on the common occurrence of abundant species of *Elphidium*. It is possible, therefore, that the Herschel Island Formation is part of the Iperk Sequence (and Nuktak Formation).

The Iperk Sequence is present in the offshore Banks-Beaufort Basin, but on reflection seismic data it is not always possible to segregate from underlying strata (Fig. 8). Iperk strata thin rapidly landward to a zero edge. Vincent et al. (1983) identified the Worth Point Formation between the Beaufort Formation below and overlying glacial deposits. Although the age of the Worth Point Formation is not well defined from indigenous fossils, it has been estimated as approximately Late Pliocene to Early Pleistocene (Matthews, 1989). Its stratigraphic position and apparent age suggest that the Worth Point Formation is equivalent to the Iperk Sequence, and, if correlated correctly, represents the only known exposure of the sequence on Banks Island.

In the Beaufort-Mackenzie Basin, Iperk strata consist of weakly consolidated to unconsolidated sandstone and conglomerate at the basin margins, grading laterally into a succession with more shale. In the mid- to outer-shelf areas the vertical succession of strata consists of a basal interval of interbedded sandstone and shale overlain by a clay- and silt-dominant interval, capped in turn by sandstone. These three lithological assemblages are bottomset, foreset, and topset deposits, respectively, and the foresets can be directly correlated to clinoforms on reflection seismic profiles. Shelf sediments contain an abundance of bivalve and gastropod shell fragments. Well preserved, reworked Mesozoic foraminifers and palynomorphs are common in the Iperk succession; in fact, it is one of the sequence's characteristics. Carbonate material, of diagenetic origin, is a common component, present as microscopic spheres and platy material (Dixon et al., 1982). A thin bed of diagenetic carbonate is commonly present underlying the unconformity in some of the farthest offshore wells (e.g., Nektoralik K-59, Dixon and Snowdon, 1979) and is probably similar in origin to hardgrounds in carbonate sediments. In the Banks-Beaufort Basin, the only lithological information comes from the Worth Point Formation, which consists of sand and gravel.

The Iperk Sequence is a relatively unstructured prograding wedge of sediment that has formed the modern continental shelf and slope. At the basin margins the Iperk Sequence consists of subparallel to slightly diverging, discontinuous reflections of low amplitude. Basinward, the reflections dip into clinoforms and the foreset reflections tend to be discontinuous and moderate to high amplitude. Bottomset reflections also tend to be discontinuous and are subparallel to hummocky, low to moderate amplitude (Figs. 6, 10, 30). The same prograding geometry is not seen offshore Banks Island because the existing seismic profiles do not extend far enough basinward.

Although we have classified the Iperk succession as a single, large-scale sequence, several internal sequences are probably present. It is apparent from some reflection profiles that during the deposition of Iperk strata the continental slope underwent several phases of development (Fig. 7). For example, there were periods of lateral progradation with minimal aggradation, and periods when progradation and aggradation were equally active. These phases of slope development have yet to be correlated on a basin-wide scale; hence the preference to regard the succession as one sequence for the present discussion.

Also, unlike some of the older sequences that have depocentres in both basins, the Iperk sequence was deposited as one, very large complex that extended northeastward along the continental margin across both the Beaufort-Mackenzie and Banks-Beaufort basins.

The Iperk Sequence thickens from a zero edge on the landward side of the basins to over 4000 m in the vicinity of the Kenalooak J-94 well (Fig. 64). There is a prominent hinge line across which Iperk strata rapidly thicken. This hinge is approximately parallel to the Tarsiut Fault Zone in the central Beaufort Sea and then swings northeastward parallel to the Inner Arctic Platform Hinge Line (Fig. 3). Iperk strata thin rapidly westward and are represented by a relatively thin section in the west Beaufort (Fig. 64). In the Mackenzie Trough, Iperk strata have been eroded and the younger Shallow Bay Sequence rests erosionally on pre-Iperk beds.

Depositional environments

The Iperk Sequence was deposited as a very large delta complex centred over the eastern Beaufort Sea and extending across two basins (Fig. 65). As previously mentioned, it appears that there was no differentiation into two depositional basins during Iperk deposition. The landward part of the sequence contains fluvial conglomerates and sandstones, grading laterally into deltaic and shelf sandstone and shale, in turn grading into and overlying slope shale and siltstone. Sandy shelf strata extend to the shelf margin and upper slope. The base-of-slope beds, consisting of interbedded sandstone and shale, probably represent small submarine fan deposits, or possibly slope apron deposits.

The distribution of facies and isopach trends (Figs. 64, 65) indicate that the major source of sediment entering the basin lay to the southeast. It is possible that Late Miocene tectonism had produced regional uplift in the northern Yukon area, resulting in the shift in pattern of river drainage toward the east. The large volume of sediment and the abundance of coarse material point to a river system that was highly competent.

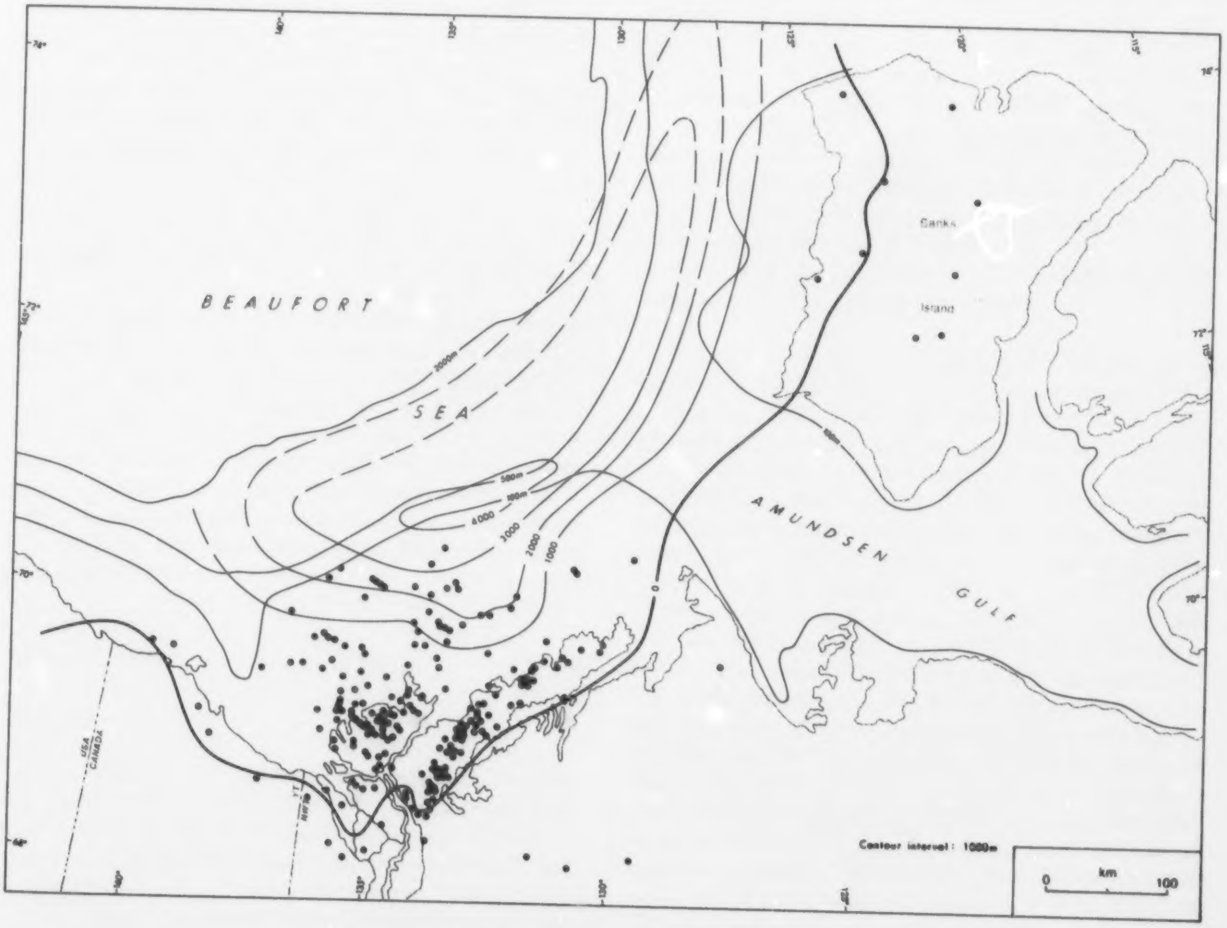

Figure 64. Isopach map, Iperk Sequence.

Age and correlation

Iperk strata contain foraminifers of the *Cribroelphidium* Assemblage Zone (formerly *Elphidium* Assemblage Zone) (Young and McNeil, 1984; McNeil, 1985; McNeil, 1989). The interval zones *Cibicides grossus* and *Cribroelphidium ustualatum* occur within the Iperk Sequence and indicate a Pliocene to Pleistocene age (McNeil, 1989). The flora is not particularly distinctive and contains elements that are extant today, as well as elements from the Miocene.

As previously discussed, the Iperk Sequence probably is equivalent to the Worth Point and Herschel Island formations in northern Canada. Although the Sagavanirktok Formation of northeast Alaska has been indicated as extending into the Pliocene (Bird and Molenaar, 1987), recent work has shown that the uppermost beds, the Nuwok Member, are only Miocene in age (McNeil and Miller, in press). The Gubik Formation of northwestern and north-central Alaska probably is equivalent to the Iperk Sequence (Bird and Molenaar, 1987).

Shallow Bay Sequence

Description and distribution

The Shallow Bay Sequence is the youngest identifiable seismic sequence on conventional multifold reflection seismic data. However, using shallow, high resolution seismic data it is possible to define more detailed internal units (S. Blasco, pers. comm., 1988). For the purposes of the present discussion, in which conventional seismic data were used, the Shallow Bay succession will be regarded as one sequence. The sequence is best seen in the Mackenzie Trough, where it rests erosionally on older strata and is up to 400 m thick. Adlartok P-09 was drilled on the northeast flank

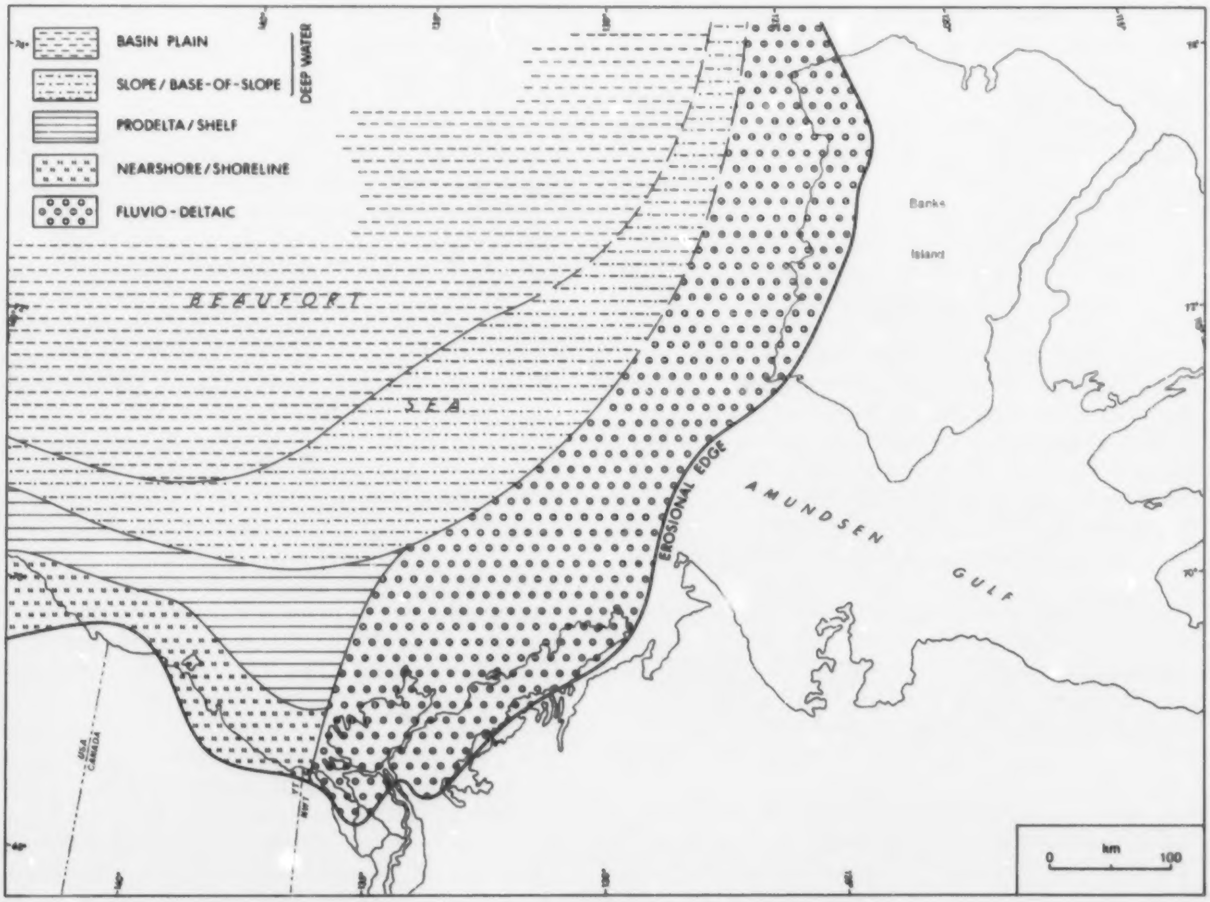

Figure 65. Interpreted Iperk Sequence depositional environments at time of maximum progradation.

of Mackenzie Trough and penetrated about 330 m of Shallow Bay strata (Fig. 9). In the Mackenzie Trough, the sequence is characterized by low amplitude, discontinuous, subparallel reflections. Elsewhere, on the shelf areas, Shallow Bay strata are impossible to separate from the underlying Iperk Sequence on conventional seismic profiles, and high resolution data are required. A thin veneer of Shallow Bay strata, probably less than 50 m thick, extends across most of the shelf areas and thickens in the slope and deep water environments. Details of the lithological succession are lacking, but in general the sequence contains a mixture of gravel, sand and mud (Vilks et al., 1979). Sediments of the modern Mackenzie Delta are included in the Shallow Bay Sequence.

Depositional environments

Details of the lithological succession and internal depositional geometry are lacking; consequently, a detailed discussion of the distribution of depositional environments is not possible. Presumably the uppermost beds reflect the modern setting; however, the deeper beds may reflect a much different environmental setting, especially if sea level were much lower.

Age and correlation

Dietrich et al. (1985) originally considered the Shallow Bay Sequence to be postglacial, and therefore mostly Holocene in age. However, it is now recognized that the internal stratigraphy may be more complex and that Pleistocene glacial and interglacial deposits may be included in the sequence (S. Blasco, pers. comm., 1988). The Shallow Bay Sequence includes the Holocene *Cassidulina reniforme* Interval Zone, which was previously included in the Plio-Pleistocene Iperk Sequence by McNeil (1989).

CONCLUSIONS

Depositional history

Cenomanian to Holocene deposition in the Porcupine-Mackenzie, Beaufort-Mackenzie and Banks-Beaufort basins is characterized by a series of oceanward prograding sequences, many of which are dominated by large delta complexes. Within the Cenomanian to Holocene succession, regional unconformities and hiatal/flooding surfaces can be correlated that allow the strata to be differentiated into at least eleven second- or third-order transgressive-regressive sequences. All eleven sequences have been identified in the Beaufort-Mackenzie Basin but the other two basins contain fewer sequences as a result of several periods of extensive erosion and nondeposition.

Deposition in these northern basins was strongly influenced by two major tectonic events — the Laramide Orogeny (Late Cretaceous to early Tertiary), and the formation of Canada Basin (?Late Cretaceous). Compression-dominant tectonics in the Cordillera created the uplifted hinterland needed to supply the large amounts of sediment that were deposited in the Porcupine-Mackenzie and Beaufort-Mackenzie basins. Banks-Beaufort Basin is not associated with an orogen; consequently, the volume of sediment is considerably less than in the Beaufort-Mackenzie Basin.

During the Cenomanian to early Tertiary, the basin margins of Canada Basin were drifting apart and thermally subsiding (Embry and Dixon, 1990). Subsidence and a large sediment load created the right combination of conditions for the accumulation of 12 to 16 km of Cenomanian to Holocene strata in the Beaufort-Mackenzie Basin (Fig. 15). In addition, the western part of the Beaufort-Mackenzie Basin was subjected to several periods of compressional deformation during the early Tertiary, and the resulting tectonic loading may have caused additional subsidence of the continental margin.

There were two distinct phases of deposition: a Cenomanian to Campanian phase, and a late Maastrichtian to Holocene phase. During the older phase, the locus of deltaic deposition was on the mainland craton, in a foredeep in front of the rising Cordillera, whereas in the Beaufort-Mackenzie and Banks Island areas, thin, organic-rich, condensed beds were being deposited. In the Banks Island area there are no data to indicate where the coeval littoral deposits were located. Because the Banks Island area was not associated with an orogen, it is unlikely that there was a thick accumulation of littoral sediments. The preserved thickness of Cenomanian to Campanian foredeep sediments in the Porcupine-Mackenzie Basin, on Eagle Plain, is in the order of 1300 m, which is about the right order of magnitude for the estimated total thickness (Dixon, in press b). This thin foreland basin fill probably reflects a relatively small amount of tectonic loading and a large areal spread of the sediments. Late Cretaceous time was also a period of widespread sea-level highstands, which were characterized by stratified oceanic water masses, low oxygen substrates, and black, organic-rich shale deposition on a global scale.

During the late Maastrichtian there was a dramatic switch to deposition on the continental margin of Canada Basin. This can be accounted for by several factors:

1. The northward migration of the Cordilleran deformation front. However, this cannot be directly related to the Banks-Beaufort Basin, where there is no orogen on the cratonward side of the basin.

2. The creation of oceanic crust under Canada Basin and thermal subsidence of the continental margins. This process would affect both the Beaufort-Mackenzie and Banks-Beaufort basins. Early rapid thermal subsidence of the continental margins may have exceeded sedimentation rates and may account, in part, for the deposition of organic-rich, deep water shales during the Cenomanian to Santonian. As thermal subsidence declined in the latest Cretaceous, large delta complexes began to prograde onto the continental margin.

3. A major, relative sea-level drop in the middle or late Maastrichtian. This is evident from the presence of upper Maastrichtian submarine fan deposits of the Cuesta Creek Member (Fish River Sequence) resting unconformably on outer shelf and slope deposits of the Cenomanian to Turonian Boundary Creek Sequence.

While all three factors were contributing causes to the shift in depositional loci, only factors 2 and 3 apparently affected both offshore basins.

During the late Maastrichtian to Holocene depositional phase, sedimentation was concentrated on the relatively narrow continental margin of the Beaufort Sea. In the Beaufort-Mackenzie Basin, depocentres shifted from west to east following deposition of the Aklak Sequence. This spatial shift in deltaic deposition may be related to the impingement of the Cordilleran Laramide Orogen into the southwestern part of the basin, beginning in Eocene time. Two separate delta complexes existed in the Beaufort-Mackenzie and Banks-Beaufort basins up to at least Eocene time. Although the record of Miocene delta sediments in the Beaufort-Mackenzie Basin is poor, the isopach trends of Miocene strata indicate that depocentres switched back far to the west. The Miocene record in the Banks-Beaufort Basin is poor, thus little is known about this period of time on Banks Island. During the Pliocene the depocentre reverted back to the eastern part of the Beaufort Sea, straddling both the Beaufort-Mackenzie and Banks-Beaufort basins; two separate depositional basins apparently were not present during this time. Since the Late Pleistocene, deltaic sedimentation has been concentrated in the Beaufort-Mackenzie Basin, with only a minor supply of sediment into the Banks-Beaufort Basin.

The Paleocene to Oligocene deltas appear to have been wave-modified, river-dominant deltas (Galloway, 1975). Only the Taglu gas field and Amauligak oil field offer sufficently close well spacing to examine in detail a specific phase of delta development. Correlations and facies analysis of the Taglu and Amauligak strata, especially the former (Dixon, 1981), indicate that delta front beds are present over a broad area and contain sedimentary features that could be attributed to storm modification. Similar log signatures and lithological successions in other lower Tertiary deltaic sequences suggest that wave-modified, river-dominant deltas prevailed from the Paleocene to the Oligocene. However, the delta complex of the Paleocene Fish River Sequence appears to have covered a larger area than the younger Paleocene to Oligocene deltas. It is possible that the Fish River delta complex was an amalgamation of two or more individual deltas, but our lack of data does not allow us to confirm such speculation. Characteristics of Miocene deltas are unknown because of a lack of known Miocene deltaic strata. Iperk deltaic strata occupy a very large area, but as indicated in the section on the Iperk Sequence, there are probably several smaller scale sequences within the succession and any comparison of delta styles with older sequences is difficult.

In the central and western parts of the Beaufort-Mackenzie Basin, syndepositional deformation of individual structures can be recognized on reflection seismic profiles. The most intense deformation appears to have occurred during deposition of the Taglu Sequence (mostly during the Middle Eocene). Middle Eocene deformation is reflected in the Taglu/Richards sequence boundary, which is a major tectonostratigraphic event within the Beaufort-Mackenzie Basin. The Talgu/Richards sequence boundary separates highly deformed strata below from less intensely deformed strata above. Deformation and syndepositional growth were less intense during the Oligocene to Miocene and virtually ceased during the Pliocene. The Late Miocene unconformity (sub-Iperk) marks the last significant phase of basin margin erosion and local deformation in the basin. The development of the Late Miocene unconformity has been partly attributed to a major eustatic sea-level fall (e.g., McNeil et al., 1982).

Deformation style and intensity change eastward and northeastward, from the asymmetrically folded and faulted anticlines in the west Beaufort, to listrically faulted strata in the central Beaufort, to essentially undeformed strata in the eastern Beaufort-Mackenzie Basin and Banks-Beaufort Basin. In the last two areas, the succession is affected by a few normal faults extending through the Paleozoic and Mesozoic succession, and very broad, gentle warping of strata. Gravity-induced faulting, commonly found in deltaic complexes, is less prevalent in the eastern Beaufort-Mackenzie Basin and Banks-Beaufort Basin than in the central Beaufort-Mackenzie Basin. The changing style and intensity of deformation is principally a function of distance from the Cordilleran orogenic front.

Origin of the sequences

When Vail et al. (1977) first introduced the concept of depositional sequences, they recognized that there were several variables, such as sediment supply, rate of subsidence (tectonics) and eustasy, that could influence the origin and development of sequences. They concluded that eustatic change was the primary controlling factor and continued to reiterate this conclusion in later work (e.g., Haq et al, 1987; Posamentier et al., 1988; Posamentier and Vail, 1988). However, other workers have argued that tectonic activity is the major control in the development of unconformity-bounded sequences (e.g., Bally, 1982; Cloetingh, 1986).

Dixon (1986) attempted to match the Beaufort-Mackenzie sequences (essentially transgressive-regressive cycles) with the coastal onlap curves of Vail et al. (1977). Subsequently, Haq et al. (1987) published a more refined onlap/eustatic curve for the Tertiary. However, the newer, detailed curves have not changed the original comparisons, other than our recognition of an additional sequence within the Eocene of the Beaufort-Mackenzie Basin. Because of the limitations of the biostratigraphic data available for the Tertiary of northern Canada, Dixon's comparisons must be viewed as a "best fit" approach. Unconformities in the Beaufort-Mackenzie and Banks-Beaufort basins that could possibly be matched to Haq et al.'s (op. cit.) curves with a fair degree of confidence include the sub-Iperk unconformity (the major 5.5 Ma Messinian unconformity); the sub-Kugmallit unconformity (the 36 Ma Eocene-Oligocene boundary unconformity); and the sub-Fish River unconformity (the 68 Ma Maastrichtian unconformity).

While Vail and his co-workers emphasize the eustatic origin of depositional sequences it must be noted that in the Beaufort-Mackenzie Basin, many of the sequence boundaries developed during periods of deformation. It is interesting to note that the three events we feel can be correlated with the Haq et al. (1987) sea-level curves are associated with major unconformities that appear to be tectonically controlled in the Beaufort-Mackenzie area. Also, each of the three unconformities are overlain by major submarine fan accumulations. In the Beaufort-Mackenzie Basin, the effects of orogeny and eustasy are difficult, if not impossible, to separate. The pronounced relationship between the Beaufort-Mackenzie sequences and deformation tends to favour tectonism as the primary control on the origin of the sequences.

REFERENCES

Balkwill, H.R., Cook, D.G., Detterman, R.L., Embry, A.F., Hakansson, E., Miall, A.D., Poulton, T.P., and Young, F.G.
1983: Arctic North America and northern Greenland. *In* Phanerozoic of the World II, Mesozoic A, Mesozoic of Arctic North America and Greenland, M. Moullade and A.E.M. Nairn (eds.); Elsevier Publishing Co., p. 1-31.

Bally, A.W.
1982: Musings over sedimentary basin evolution. Philosophical Transactions of the Royal Society of London, Series A, v. 305, p. 325-338.

Bamber, E.W.
1973: Description of Carboniferous and Permian stratigraphic sections, northern Yukon Territory and northwestern District of Mackenzie (N.T.S. 106 M; 116 C, F, G, H, I, J, P; 117 A, B, C). Geological Survey of Canada, Paper 72-19, 61 p.

Bamber, E.W. and Waterhouse, J.B.
1971: Carboniferous and Permian stratigraphy and paleontology, northern Yukon Territory, Canada. Bulletin of Canadian Petroleum Geology, v. 14, p. 29-250.

Bates, R.L. and Jackson, J.A.
1980: Glossary of Geology. Second Edition. American Geological Institute, Falls Church, Virginia.

Baxter, A.J. and Cheadle, B.A.
1989: The sequence stratigraphy of the Kugmallit Formation, Mackenzie Delta, Northwest Territories, Canada. (Abstract) Canadian Society of Exploration Geophysicists-Canadian Society of Petroleum Geologists, Exploration Update '89, Program and Abstracts, p. 51.

Bird, K.J. and Molenaar, C.M.
1987: Stratigraphy. *In* Petroleum Geology of the Northern Part of the Arctic National Wildlife Refuge, Northeastern Alaska, K.J. Bird and L.B. Magoon (eds.); US Geological Survey, Bulletin 1778, p. 37-59.

Bornhold, B.D., Buckley, D.E., Costaschuk, S., Forbes, D.L., Lewis, C.F.M., Lewis, C.P., Matsumoto, E., Meagher, L., Pelletier, B.R., Walker, D.A., and Wong, C.S.
1984: Marine Science Atlas of the Beaufort Sea: Sediments. Energy, Mines and Resources Canada, 27 p.

Bowerman, J.N. and Coffman, R.C.
1975: The geology of the Taglu gas field in the Beaufort Basin, N.W.T. *In* Canada's Continental Margins and Offshore Petroleum Exploration, C.J. Yorath, E.R. Parker, and D.J. Glass (eds.); Canadian Society of Petroleum Geologists, Memoir 4, p. 649-662.

Brideaux, W.W. and Myhr, D.W.
1976: Lithostratigraphy and dinoflagellate cyst succession in the Gulf Mobil Parsons N-10 well, District of Mackenzie. *In* Report of Activities, Part B, Geological Survey of Canada, Paper 76-1B, p. 235-249.

Bujak, J.P. and Davies, E.H.
1981: Neogene dinoflagellate cysts from the Hunt Dome Kopanoar M-13 well, Beaufort Sea, Canada. Bulletin of Canadian Petroleum Geology, v. 29, p. 420-425.

Carey, S.W.
1958: A tectonic approach to continental drift. *In* Continental Drift, a Symposium, S.W. Carey (ed.); University of Tasmania, p. 177-355.

Chamney, T.P.
1969: Abnormally thick Tertiary-Cretaceous sequence, Mackenzie Delta, District of Mackenzie. *In* Report of Activities, Part B, Geological Survey of Canada, Paper 69-1B, p. 69-72.

1972: Biostratigraphic contributions from the Arctic Coastal Plain west of the Mackenzie Delta. *In* Report of Activities, Part A, Geological Survey of Canada, Paper 72-1A, p. 202, 203.

1973: Tuktoyaktuk Peninsula Tertiary and Mesozoic biostratigraphy correlations. *In* Report of Activities, Geological Survey of Canada, Paper 73-1B, p. 171-178.

Cloetingh, S.
1986: Intraplate stresses: a new tectonic mechanism for fluctuations of relative sea-level. Geology, v. 14, p. 617-621.

Cook, F.A., Coflin, K.C., Lane, L.S., Dietrich, J.R., and Dixon, J.
1987a: Preliminary interpretations of the Mackenzie-Beaufort Basin deep crustal reflection survey. Geological Survey of Canada, Open File 1549.

1987b: Structure of the southeast margin of the Beaufort-Mackenzie basin, Arctic Canada, from crustal seismic reflection data. Geology, v. 15, p. 931-935.

Cote, R.P., Lerand, M.M., and Rector, R.J.
1975: Geology of the Lower Cretaceous Parsons Lake gas field, Mackenzie Delta, Northwest Territories. *In* Canada's Continental Margins, C.J. Yorath, E.R. Parker, and D.J. Glass (eds.); Canadian Society of Petroleum Geologists, Memoir 4, p. 613-632.

Dietrich, J.R., Dixon, J., and McNeil, D.H.
1985: Sequence analysis and nomenclature of Upper Cretaceous to Holocene strata in the Beaufort-Mackenzie Basin. *In* Current Research, Part A, Geological Survey of Canada, Paper 85-1A, p. 613-628.

Dietrich, J.R., Dixon, J., McNeil, D.H., McIntyre, D.J., Snowdon, L.R., and Cameron, A.R.
1989: Geology, biostratigraphy and organic geochemistry of the Natsek E-56 and Edlok N-56 wells, Beaufort Sea, Arctic Canada. *In* Current Research, Part G, Geological Survey of Canada, Paper 89-1G, p. 133-157.

Dixon, J.
1979: The Lower Cretaceous Atkinson Point Formation (new name) on the Tuktoyaktuk Peninsula, N.W.T.: A coastal fan-delta to marine sequence. Bulletin of Canadian Petroleum Geology, v. 27, p. 163-182.

1981: Sedimentology of the Eocene Taglu Delta, Beaufort-Mackenzie Basin: example of a river-dominant delta. Geological Survey of Canada, Paper 80-11, 11 p.

1982: Jurassic and Lower Cretaceous subsurface stratigraphy of the Mackenzie Delta-Tuktoyaktuk Peninsula, N.W.T. Geological Survey of Canada, Bulletin 349, 52 p.

1986: Cretaceous to Pleistocene stratigraphy and paleogeography, northern Yukon and northwestern District of Mackenzie. Bulletin of Canadian Petroleum Geology, v. 34, p. 49-70.

1988: Depositional setting of the Maastrichtian Cuesta Creek Member, Tent Island Formation, northern Yukon. *In* Current Research, Part D, Geological Survey of Canada, Paper 88-1D, p. 61-66.

in press a: Cretaceous tectonics and sedimentation in northwest Canada. *In* Evolution of the Western Interior Foreland Basin, W.G.E. Caldwell (ed.); Geological Association of Canada, Special Paper.

in press b: Mesozoic stratigraphy, Eagle Plain area, northern Yukon. Geological Survey of Canada, Bulletin 408.

Dixon, J. and Dietrich, J.R.

1988: The nature of depositional and seismic sequence boundaries in Cretaceous-Tertiary strata of the Beaufort-Mackenzie Basin. *In* Sequences, Stratigraphy, Sedimentology: Surface and Subsurface, D.P. James and D.A. Leckie (eds.); Canadian Society of Petroleum Geologists, Memoir 15, p. 63-72.

1990: Canadian Beaufort Sea and adjacent land areas. *In* The Arctic Ocean Region, A. Grantz, L. Johnson, and J.F. Sweeney (eds.); Geological Society of America, The Geology of North America, v. L, ch. 16, p. 239-256.

Dixon, J., Dietrich, J.R., McNeil, D.H., McIntyre, D.J., Snowdon, L.R., and Brooks, P.

1985: Geology, biostratigraphy and organic geochemistry of Jurassic to Pleistocene strata, Beaufort-Mackenzie area, northwest Canada. Canadian Society of Petroleum Geologists, Course Notes, 65 p.

Dixon, J.D., McNeil, D.H., Dietrich, J.R., Bujak, J.P., and Davies, E.H.

1984: Geology and biostratigraphy of the Dome Gulf et al. Hunt Kopanoar M-13 well, Beaufort Sea. Geological Survey of Canada, Paper 82-13, 28 p.

Dixon, J., McNeil, D.H., and Michael, G.P.

1982: A brief description of calcite spheres from Pliocene strata in the Dome Gulf et al. C-50 well, Beaufort Sea, Arctic Canada. Canadian Journal of Earth Sciences, v. 19, p. 623-628.

Dixon, J. and Snowdon, L.R.

1979: Geology and organic geochemistry of the Dome Hunt Nektoralik K-59 well, Beaufort Sea. *In* Current Research, Part C, Geological Survey of Canada, Paper 79-1C, p. 85-90.

Doerenkamp, A., Jardine, S., and Moreau, P.

1976: Cretaceous and Tertiary palynomorph assemblages from Banks Island and adjacent areas (N.W.T.). Bulletin of Canadian Petroleum Geology, v. 24, p. 372-417.

Embry, A.F.

1983: Depositional sequences-impractical lithostratigraphic units (Abstract). Geological Society of America, Abstracts with Program, p. 567.

1989: A tectonic origin for third-order depositional sequences in extensional basins-implications for basin modelling. *In* Quantitative Dynamic Stratigraphy, T.A. Cross (ed.); Prentice Hall, p. 491-501.

in press: Mesozoic history of the Arctic Islands. *In* Innuitian Orogen and Arctic Platform: Canada and Greenland, H.P. Trettin (ed.); Geological Survey of Canada, Geology of Canada, no. 3 [Also Geological Society of America, The Geology of North America, v. E.]

Embry, A.E. and Dixon, J.

1990: The breakup unconformity of the Amerasia Basin, Arctic Ocean: evidence from Arctic Canada. Geological Society of America, Bulletin, v. 102, p. 1526-1534.

Embry, A.E. and Podruski, J.A.

1988: Third-order depositional sequences of the Mesozoic succession of Sverdrup Basin. *In*

Sequences, Stratigraphy, Sedimentology: Surface and Subsurface, D.P. James and D.A. Leckie (eds.); Canadian Society of Petroleum Geologists, Memoir 15, p. 73-84.

Frazier, D.E.
1974: Depositional episodes: their relationship to the Quaternary stratigraphic framework in the northwestern portion of the Gulf Basin. Bureau of Economic Geology, The University of Texas at Austin, Austin, Texas, Geological Circular 74-1, 28 p.

Fyles, J.G.
1966: Quaternary stratigraphy. *In* Report of Activities, May to October, 1965, Mackenzie Delta and Arctic Coastal Plain. Geological Survey of Canada, Paper 66-1, p. 30, 31.

1967: Mackenzie Delta and Arctic Coastal Plain. *In* Report of Activities, Geological Survey of Canada, Paper 67-1A, p. 34, 35.

Galloway, W.E.
1975: Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. *In* Deltas: Models for Exploration, M.L.S. Broussard (ed.); Houston Geological Society, p. 87-98.

1989: Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units. American Association of Petroleum Geologists, Bulletin, v. 73, p. 125-142.

Gardner, D.A.C. and Bates, A.C.
1987: Application of seismic stratigraphy to tectonic and facies interpretation of Tertiary sediments in the Canadian Beaufort Sea. Proceedings 12th World Petroleum Congress, v. 2, Exploration, p. 179-188.

Glaister, R.P. and Hopkins, J.C.
1974: Turbidity-current and debris-flow deposits. *In* Use of Sedimentary Structures for Recognition of Clastic Environments, M.S. Shawa (ed.); Canadian Society of Petroleum Geologists, p. 23-40.

Grantz, A., Ettreim, S., and Dinter, D.A.
1979: Geology and tectonic development of the continental margin north of Alaska. Tectonophysics, v. 59, p. 263-291.

Grantz, A., Ettreim, S., and Whitney, O.T.
1981: Geology and physiography of the continental margin north of Alaska. *In* Studies in Continental Margin Geology, J.S. Watkins and C.L. Drake (eds.); American Association of Petroleum Geologists, Memoir 34, p. 77-100.

Grond, H.C., Churchill, S.J., Armstrong, R.L., Harakal, J.E., and Nixon, G.T.
1984: Late Cretaceous age of the Hutshi, Mount Nansen, and Carmacks groups, southwestern Yukon Territory and northwestern British Columbia. Canadian Journal of Earth Sciences, v. 21, p. 554-558.

Gryc, G. (editor)
1988: Geology and exploration of the National Petroleum Reserve in Alaska, 1974 to 1982. United States Geological Survey, Professional Paper 1399, 940 p.

Hawkings, T.J. and Hatlelid, W.G.
1975: The regional setting of the Taglu gas field. *In* Canada's Continental Margins and Offshore Petroleum Exploration, C.J. Yorath, E.R. Parker, and D.J. Glass (eds.); Canadian Society of Petroleum Geologists, Memoir 4, p. 633-647.

Haq, B.U., Hardenbol, J., and Vail, P.R.
1987: Chronology of fluctuating sea-levels since the Triassic (250 million years ago to present). Science, v. 235 (4793), p. 1156-1167.

Hea, J.P., Arcuri, J., Campbell, G.R., Fraser, I., Fuglem, M.O., O'Bertos, J.J., Smith, D.R., and Zayat, M.
1980: Post Ellesmerian basins in Arctic Canada; their depocentres, rates of sedimentation and petroleum potential. *In* Facts and Principles of World Oil Occurrence, A.D. Miall (ed.); Canadian Society of Petroleum Geologists, Memoir 6, p. 447-488.

Heritier, F.E., Lossel, P., and Wathne, E.
1979: Frigg Field – large submarine fan trap in Lower Eocene rocks of North Sea Viking Graben. American Association of Petroleum Geologists, Bulletin, v. 63, p. 1999-2020.

1981: The Frigg gas field. *In* Petroleum Geology of the Continental Shelf of North-West Europe, L.V. Illing and G.D. Hobson (eds.); Institute of Petroleum Geology, published by Heyden and Son Ltd., p. 380-391.

Hills, L.V.
1969: Beaufort Formation, northwestern Banks Island, District of Franklin. *In* Report of Activities, Part A, Geological Survey of Canada, Paper 69-1A, p. 204-207.

Hills, L.V. and Fyles, J.G.
1973: The Beaufort Formation, Canadian Arctic Islands. (Abstract). Program and Abstracts, Symposium on the Geology of the Canadian Arctic, Canadian Society of Petroleum Geologists and Geological Association of Canada, p. 11.

Hills, L.V., Klovan, J.E., and Sweet, A.R.
1974: *Juglans eocinera* n.sp. Beaufort Formation (Tertiary), southwestern Banks Island, Arctic Canada. Canadian Journal of Botany, v. 52, p. 65-90.

Hofer, H. and Varga, W.
1972: Seismogeologic experience in the Beaufort Sea. Geophysics, v. 37, p. 605-619.

Holmes, D.W. and Oliver, T.A.
1973: Source and depositional environments of the Moose Channel Formation, Northwest Territories. Bulletin of Canadian Petroleum Geology, v. 21, p. 435-478.

Hughes, O.L.
1972: Surficial geology of northern Yukon Territory and northwestern District of Mackenzie, Northwest Territories. Geological Survey of Canada, Paper 69-36, 11 p.

Ioannides, N.S. and McIntyre, D.J.
1980: A preliminary palynological study of the Caribou Hills outcrop section along the Mackenzie River, District of Mackenzie. *In* Current Research, Part A, Geological Survey of Canada, Paper 82-1A, p. 197-208.

James, D.P. and Baxter, A.J.
1988: Stratigraphy and sedimentology of the Kugmallit Formation, Nipterk structure: Beaufort–Mackenzie Basin, Canada. *In* Sequences, Stratigraphy, Sedimentology: Surface and Subsurface, D.P. James and D.A. Leckie (eds.); Canadian Society of Petroleum Geologists, Memoir 15, p. 117-136.

Jeletzky, J.A.
1960: Uppermost Jurassic and Cretaceous rocks, west flank of Richardson Mountains between Stony Creek and lower Donna River, Northwest Territories. Geological Survey of Canada, Paper 59-14, 31 p.

1972: Stratigraphy, facies and paleogeography of Mesozoic and Tertiary rocks of northern Yukon and northwest Mackenzie District, N.W.T. (NTS-197 B, 106 M, 117 A, 116 O N1/2). *In* Report of Activities, Part A, Geological Survey of Canada, Paper 72-1A, p. 212-215.

Johnson, B., Calverley, A.E., and Pendlebury, D.C.
1976: Pleistocene foraminifera from northern Yukon, Canada. *In* First International Symposium on Benthonic Foraminifera of Continental Margins, Part B, C.T. Schafer and B.R. Pelletier (eds.); Maritime Sediments, Special Publication No. 1, p. 393-400.

Jones, P.B., Brache, J., and Lentin, J.K.
1980: The geology of the 1977 offshore hydrocarbon discoveries in the Beaufort–Mackenzie Basin, N.W.T. Bulletin of Canadian Petroleum Geology, v. 28, p. 81-102.

Lane, F.H. and Jackson, K.S.
1980: Controls on occurrences of oil and gas in the Beaufort–Mackenzie Basin. *In* Facts and Principles of World Oil Occurrence, A.D. Miall (ed.); Canadian Society of Petroleum Geologists, Memoir 6, p. 489-501.

Lane, L.S.
1988: The Rapid Fault Array: a foldbelt in Arctic Yukon. *In* Current Research, Part D, Geological Survey of Canada, Paper 88-1D, p. 95-98.

Lane, L.S. and Cecile, M.P.
1989: Stratigraphy and structure of the "Neruokpuk Formation", northern Yukon. *In* Current Research, Part G, Geological Survey of Canada, Paper 89-1G, p. 57-62.

L[illegible]ver, L.A., Grantz, A., and Meinke, L.
198[illegible]: The tectonics of the Arctic Ocean. *In* Arctic Technology and Policy, I. Dyer and C. Chryssostomidis (eds.); Hemisphere Publishing Corp. (also through McGraw-Hill International Book Co. outside of USA), p. 147-158.

Lerand, M.M.

1973: Beaufort Sea. *In* The Future Petroleum Provinces of Canada, R.G. McCrossan (ed.); Canadian Society of Petroleum Geologists, Memoir 1, p. 315-386.

Mackay, J.R.

1963: The Mackenzie Delta area, N.W.T. Canada Department of Mines and Technical Surveys, Geographic Branch, Memoir 8, 202 p.

Matthews, J.V. Jr.

1989: New information on the flora and age of the Beaufort Formation, Arctic Archipelago, and related Tertiary deposits in Alaska. *In* Current Research, Part D, Geological Survey of Canada, Paper 89-1D, p. 105-111.

Matthews, W.H. and Bustin, R.M.

1984: Why do the Smoking Hills smoke? Canadian Journal of Earth Sciences, v. 21, p. 737-742.

McIntyre, D.J.

1974: Palynology of an Upper Cretaceous section, Horton River, District of Mackenzie, N.W.T. Geological Survey of Canada, Paper 74-14, 57 p.

1985: Palynology. *In* Geology, Biostratigraphy and Organic Geochemistry of Jurassic to Pleistocene Strata, Beaufort-Mackenzie Area, Northwest Canada. J. Dixon, J.R. Dietrich, D.H. McNeil, D.J. McIntyre, L.R. Snowdon, and P. Brooks, Course Notes, Canadian Society of Petroleum Geologists, p. 39-50.

McNeil, D.H.

1983: *Jadammina statuminis*, n.sp., in the Eocene Richards shale, Mackenzie Delta area of Arctic Canada. Journal of Foraminiferal Research, v. 13, p. 219-223.

1985: Tertiary foraminiferal biostratigraphy of the Beaufort-Mackenzie Basin. *In* Geology, Biostratigraphy and Organic Geochemistry of Jurassic to Pleistocene Strata, Beaufort-Mackenzie Area, Northwest Canada, J. Dixon, J.R. Dietrich, D.H. McNeil, D.J. McIntyre, L.R. Snowdon, and P. Brooks,Course Notes, Canadian Society of Petroleum Geologists, p. 32-38.

1989: Foraminiferal zonation and biofacies analysis of Cenozoic strata in the Beaufort-Mackenzie Basin of Arctic Canada. *In* Current Research, Part G, Geological Survey of Canada, Paper 89-1G, p. 203-223.

1990: Stratigraphy and paleoecology of the Eocene *Stellarima* Assemblage Zone (pyrite diatom steinkerns) in the Beaufort-Mackenzie Basin, Arctic Canada. Bulletin of Canadian Petroleum Geology, v. 38, p. 17-27.

McNeil, D.H., Ioannides, N.S., and Dixon, J.

1982: Geology and biostratigraphy of the Dome Gulf et al. Ukalerk C-50 well, Beaufort Sea. Geological Survey of Canada, Paper 80-32, 17 p.

McNeil, D.H. and Miller, K.G.

in press: High latitude application of ^{87}Sr/^{86}Sr - correlation of Nuwok beds on the North Slope, Alaska, to standard Oligocene chronostratigraphy. Geology.

McWhae, J.R.

1986: Tectonic history of northern Alaska, Canadian Arctic, and Spitsbergen regions since Early Cretaceous. American Association of Petroleum Geologists, Bulletin, v. 70, p. 430-450.

Miall, A.D.

1974: Bedrock geology of Banks Island. *In* Report of Activities, Part B, Geological Survey of Canada, Paper 74-1B, p. 336-342.

1975: Post-Paleozoic geology of Banks, Prince Patrick and Eglinton islands, Arctic Canada. *In* Canada's Continental Margins, C.J. Yorath, E.R. Parker, and D.J. Glass (eds.); Canadian Society of Petroleum Geologists, Memoir 4, p. 557-587.

1976: Proterozoic and Paleozoic geology of Banks Island, Arctic Canada. Geological Survey of Canada, Bulletin 258, 77 p.

1979: Mesozoic and Tertiary geology of Banks Island, Arctic Canada; the history of an unstable craton margin. Geological Survey of Canada, Memoir 387, 235 p.

1986: The Eureka Sound Group (Upper Cretaceous-Oligocene), Canadian Arctic Islands. Bulletin of Canadian Petroleum Geology, v. 34, p. 240-270.

Miall, A.D., Balkwill, H.R., and Hopkins, W.S. Jr.
1980: Cretaceous and Tertiary sediments of Eclipse Trough, Bylot Island area, Arctic Canada, and their regional setting. Geological Survey of Canada, Paper 79-23, 19 p.

Mitchum, R.M. Jr., Vail, P.R., and Thompson, S. III.
1977: Seismic stratigraphy and global changes of sea-level, Part 2: The depositional sequence as a basic unit for stratigraphic analysis. *In* Seismic Stratigraphy-Applications to Hydrocarbon Exploration, C.E. Payton (ed.); American Association of Petroleum Geologists, Memoir 26, p. 53-62.

Molenaar, C.M.
1983: Depositional relations of Cretaceous and lower Tertiary rocks, northeastern Alaska. American Association of Petroleum Geologists, Bulletin, v. 67, p. 1066-1080.

Morrell, G.R. and Schmidt, U.B.
1988: Subsequences of the Kugmallit delta front, Beaufort-Mackenzie Basin. *In* Sequences, Stratigraphy, Sedimentology: Surface and Subsurface, D.P. James and D.A. Leckie (eds.); Canadian Society of Petroleum Geologists, Memoir 15, p. 361-372.

Mountjoy, E.W.
1967: Upper Cretaceous and Tertiary stratigraphy, northern Yukon Territory and northwestern District of Mackenzie. Geological Survey of Canada, Paper 66-16, 70 p.

Myhr, D.W.
1975: Markers within Cretaceous rocks as indicated by mechanical logs from boreholes in the Mackenzie Delta area, Northwest Territories. *In* Report of Activities, Part B, Geological Survey of Canada, Paper 75-1B, p. 267-275.

Myhr, D.W. and Barefoot, R.R.
1976: Geochemical properties of Cretaceous rocks and their use as a correlation tool, Mackenzie Delta and Yukon Coastal Plain areas. *In* Report of Activities, Part B, Geological Survey of Canada, Paper 76-1B, p. 311-314.

Naylor, D., McIntyre, D.J., and McMillan, N.F.
1972: Pleistocene deposits exposed along the Yukon coast. Arctic, v. 25, p. 49-55.

Nentwich, F.W. and Yole, R.W.
1982: Sedimentary petrology and stratigraphic analysis of the subsurface Reindeer Formation (early Tertiary), Mackenzie Delta-Beaufort Sea area, Canada. *In* Arctic Geology and Geophysics, A.F. Embry and H.R. Balkwill (eds.); Canadian Society of Petroleum Geologists, Memoir 8, p. 55-82.

Norris, D.K.
1972: Structural and stratigraphic studies in the tectonic complex of northern Yukon Territory, north of Porcupine River. *In* Report of Activities, Part B, Geological Survey of Canada, Paper 72-1B, p. 91-99.

1981a: Geology: Herschel Island and Demarcation Point, Yukon Territory. Geological Survey of Canada, Map 1514A (scale 1:250 000).

1981b: Geology: Mackenzie Delta, District of Mackenzie. Geological Survey of Canada, Map 1515A (scale 1:250 000).

1981c: Geology: Blow River and Davidson Mountains, Yukon Territory-District of Mackenzie. Geological Survey of Canada, Map 1516A (scale 1:250 000).

1981d: Geology: Aklavik, District of Mackenzie. Geological Survey of Canada, Map 1517A (scale 1:250 000).

1981e: Geology: Old Crow, Yukon Territory. Geological Survey of Canada, Map 1518A (scale 1:250 000).

1983: Porcupine virgation – the structural link among Columbian, Innuitian and Alaskan orogens. (Abstract.) Geological Association of Canada-Mineralogical Association of Canada-Canadian Geophysical Union, Program with abstracts, v. 8, p. A51.

1985a: Eastern Cordilleran Foldbelt of northern Canada: its structural geometry and hydrocarbon potential. American Association of Petroleum Geologists, Bulletin, v. 69, p. 788-808.

1985b: The Neruokpuk Formation, Yukon Territory and Alaska. *In* Current Research, Part B, Geological Survey of Canada, Paper 85-1B, p. 223-229.

Norris, D.K. and Yorath, C.J.
1981: The North American Plate from the Arctic Archipelago to the Romanzof Mountains. *In* The Ocean Basins and Margins, v. 5, The Arctic Ocean, A.E.M. Nairn, M. Churkin, Jr., and F.G. Stehli (eds.); Plenum Press, p. 37-103.

The North American Commission on Stratigraphic Nomenclature
1983: North American Stratigraphic Code. American Association of Petroleum Geologists, Bulletin, v. 67, p. 841-875.

Pelletier, B.R. (editor)
1987: Marine Science Atlas of the Beaufort Sea: Geology and Geophysics. Geological Survey of Canada, Miscellaneous Report 40, 39 p.

Plauchut, B.D. and Jutard, G.G.
1976: Cretaceous and Tertiary stratigraphy, Banks and Eglinton islands and Anderson Plain (N.W.T.). Bulletin of Canadian Petroleum Geology, v. 24, p. 321-371.

Posamentier, H.W., Jervey, M.T., and Vail, P.R.
1988: Eustatic controls on clastic deposition I - Conceptual framework. *In* Sea-level Changes: An Integrated Approach, C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. Van Wagoner (eds.); Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 109-124.

Posamentier, H.W. and Vail, P.R.
1988: Eustatic controls on clastic deposition II - Sequence and systems tract models. *In* Sea-level Changes: An Integrated Approach, C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. Van Wagoner (eds.); Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 125-154.

Poulton, T.P.
1982: Paleogeographic and tectonic implications of the Lower and Middle Jurassic facies patterns in northern Yukon Territory and adjacent Northwest Territories. *In* Arctic Geology and Geophysics, A.F. Embry and H.R. Balkwill (eds.); Canadian Society of Petroleum Geologists, Memoir 8, p. 13-28.

Poulton, T.P., Leskiw, K., and Audretsch, A.P.
1982: Stratigraphy and microfossils of the Jurassic Bug Creek Group of northern Richardson Mountains, northern Yukon and adjacent Northwest Territories. Geological Survey of Canada, Bulletin 325, 137 p.

Price, L.L., McNeil, D.H., and Ioannides, N.S.
1980: Revision of the Tertiary Reindeer Formation in the Caribou Hills, District of Mackenzie. *In* Current Research, Part B, Geological Survey of Canada, Paper 80-1B, p. 179-184.

Pugh, D.C.
1983: Pre-Mesozoic geology in the subsurface of Peel River map area, Yukon Territory and District of Mackenzie. Geological Survey of Canada, Memoir 401, 61 p.

Rampton, V.N.
1969: Quaternary geology, Mackenzie Delta and Arctic Coastal Plain, District of Mackenzie. *In* Report of Activities, Part A, Geological Survey of Canada, Paper 70-1A, p. 181, 182.

Ricketts, B.D.
1986: New formations in the Eureka Sound Group, Canadian Arctic Islands. *In* Current Research, Part B, Geological Survey of Canada, Paper 86-1B, p. 363-374.

1988: The Monster Formation: a coastal fan system of Late Cretaceous age, Yukon Territory. Geological Survey of Canada, Paper 86-14, 27 p.

Shawa, M.S.
1979: Sedimentology and stratigraphy of the Taglu member, Mackenzie Delta. (Abstract.) Canadian Society of Petroleum Geologists, Reservoir, v. 6, p. 1, 2.

Sirrine, G.K.
1973: Tectonics of Mackenzie Delta exposed through triple survey. Oilweek, November 19, v. 24, no. 40, p. 20, 21.

Staplin, F.L. (editor)
1976: Tertiary biostratigraphy, Mackenzie Delta region, Canada. Bulletin of Canadian Petroleum Geology, v. 24, p. 117-136.

Sweet, A.R.
1978: Palynology of the lower part, type section, Tent Island Formation, Yukon Territory. *In* Current Research, Part B, Geological Survey of Canada, Paper 78-1B, p. 31-37.

Tailleur, I.L.
1973: Probable rift origin of Canada Basin, Arctic Ocean. *In* Arctic Geology, M.G. Pitcher (ed.); American Association of Petroleum Geologists, Memoir 19, p. 526-535.

Tailleur, I.L. and Brosge, W.P.
1970: Tectonic history of northern Alaska. *In* Proceedings of the geological seminar on the North Slope of Alaska, W.L. Adkinson and M.M. Brosge (eds.); Pacific Section, American Association of Petroleum Geologists, p. E1-E19.

Thorsteinsson, R. and Tozer, E.T.
1960: Summary account of structural history of the Canadian Arctic Archipelago since Precambrian time. Geological Survey of Canada, Paper 60-7, 25 p.

1962: Banks, Victoria, and Stefansson islands, Arctic Archipelago. Geological Survey of Canada, Memoir 330, 85 p.

Tozer, E.T.
1956: Geological reconnaissance, Prince Patrick, Eglinton, and western Melville islands, Arctic Archipelago, Northwest Territories. Geological Survey of Canada, Paper 55-5, 32 p.

Vail, P.R., Hardenbol, J., and Todd, R.G.
1984: Jurassic unconformities, chronostratigraphy and sea-level changes from seismic stratigraphy and biostratigraphy. *In* Interregional Unconformities and Hydrocarbon Accumulation, J.S. Schlee (ed.); American Association of Petroleum Geologists, Memoir 36, p. 129-144.

Vail, P.R. and Mitchum, R.M. Jr.
1977: Seismic stratigraphy and global changes of sea-level, Part 1: Overview. *In* Seismic Stratigraphy - Applications to Hydrocarbon Exploration, C.E. Payton (ed.); American Association of Petroleum Geologists, Memoir 26, p. 51, 52.

Vail, P.R., Mitchum, R.M. Jr., and Thompson, S. III
1977: Seismic stratigraphy and global changes of sea-level, Part 4: Global cycles of relative changes of sea-level. *In* Seismic Stratigraphy - Application to Hydrocarbon Exploration, C.E. Payton (ed.); American Association of Petroleum Geologists, Memoir 26, p. 83-97.

Vilks, G., Wagner, F.J.E., and Pelletier, B.R.
1979: The Holocene marine environment of the Beaufort shelf. Geological Survey of Canada, Bulletin 303, 43 p.

Vincent, J-S, Occhietti, S., Rutter, N., Lortie, J-P., and de Boutray, B.
1983: The late Tertiary-Quaternary stratigraphic record of the Duck Hawk Bluffs, Banks Island, Canadian Arctic Archipelago. Canadian Journal of Earth Sciences, v. 20, p. 1694-1712.

Wall, J.H., McNeil, D.H., Ricketts, B.R., and McIntyre, D.J.
1988: Paleocene foraminifera from the Eureka Sound Group, eastern Sverdrup Basin, Canadian Arctic Archipelago. (Abstract) Geological Society of America, Annual Meeting, Abstracts with Programs, v. 20, p. A222.

Wielens, J.B.W.
1987: Study of pre-Mesozoic stratigraphy and structure of Tuktoyaktuk Peninsula. Geological Survey of Canada, Open File 1513.

1988a: Study of pre-Mesozoic stratigraphy and structure of Tuktoyaktuk Peninsula, part II. Geological Survey of Canada, Open File 1811.

1988b: A brief outline of the pre-Mesozoic stratigraphy and structure of Tuktoyaktuk Peninsula, Northwest Territories. *In* Sequences, Stratigraphy, Sedimentology: Surface and Subsurface, D.P. James and D.A. Leckie (eds.); Canadian Society of Petroleum Geologists, Memoir 15, p. 517-524.

Willumsen, P.S. and Cote, R.P.
1982: Tertiary sedimentation in the southern Beaufort Sea. *In* Arctic Geology and Geophysics, A.F. Embry and H.R. Balkwill (eds.); Canadian Society of Petroleum Geologists, Memoir 8, p. 43-53.

Yorath, C.J.
1973: Geology of Beaufort-Mackenzie Basin and eastern part of Northern Interior Plains. *In* Arctic Geology, M.G. Pitcher (ed.); American Association of Petroleum Geologists, Memoir 19, p. 41-47.

Yorath, C.J., Balkwill, H.R., and Klassen, R.W.
1975: Franklin Bay and Malloch Hill map-areas, District of Mackenzie (95 C, F). Geological Survey of Canada, Paper 74-36, 35 p.

Yorath, C.J. and Cook, D.G.
1981: Cretaceous and Tertiary stratigraphy and paleogeography, Northern Interior Plains, District of Mackenzie. Geological Survey of Canada, Memoir 398, 76 p.

Yorath, C.J. and Norris, D.K.
1975: The tectonic development of the southern Beaufort Sea and its relationship to the origin of the Arctic Ocean Basin. *In* Canada's Continental Margins and Offshore Petroleum Exploration, C.J. Yorath, E.R. Parker, and D.J. Glass (eds.); Canadian Society of Petroleum Geologists, Memoir 4, p. 589-611.

Young, F.G.
1973: Mesozoic epicontinental, flyschoid and molassoid depositional phases of Yukon's North Slope. *In* Canadian Arctic Geology, J.D. Aitken and D.J. Glass (eds.); Geological Association of Canada-Canadian Society of Petroleum Geologists, p. 181-201.

1975: Upper Cretaceous stratigraphy, Yukon Coastal Plain and northwestern Mackenzie Delta. Geological Survey of Canada, Bulletin 249, 83 p.

1978: (editor) Geological and geographical guide to the Mackenzie Delta area. Canadian Society of Petroleum Geologists, 158 p.

Young, F.G. and McNeil, D.H.
1984: Cenozoic stratigraphy of the Mackenzie Delta, Northwest Territories. Geological Survey of Canada, Bulletin 336, 63 p.

Young, F.G., Myhr, D.W., and Yorath, C.J.
1976: Geology of the Beaufort-Mackenzie Basin. Geological Survey of Canada, Paper 76-11.

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